

LONGSHORE SEDIMENT TRANSPORT

IN A MIXED SAND AND GRAVEL

FORESHORE, SOUTH CANTERBURY

A thesis

submitted in partial fulfilment

of the requirements for the Degree

of

Master of Science in Geography

in the

University of Canterbury

by

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University of Canterbury

1987

FRONTISPIECE: Northeasterly swell conditions
at South Beach, Timaru.



ABSTRACT

This thesis examines the processes, patterns and rates of longshore sediment transport in the mixed sand and gravel foreshores (particle sizes 1 mm to 200 mm) of the South Canterbury coast. The beach system that is studied presents a very different situation from that most commonly studied on sand beaches. The flows of water and sediment are dominated by breaking waves and swash rather than 'surf' and interrelated subzones of distinctive processes, responses and sediment transport regimes occur across the foreshore. A variety of methods for measuring water flows and sediment movements are assessed and a set of daily beach observations made over four months is analysed. Long- and short-term net rates of longshore transport in the study area are estimated to average $51,288 \text{ m}^3 \cdot \text{yr}^{-1}$ from measurements of the historic accumulation of beach material updrift of structures at Timaru Harbour. This estimate is then used with deepwater wave data to 'calibrate' a widely used linear relationship between the transport rate and the longshore component of wave power, for use in a mixed beach situation. Short-term measurements of the transport rate and wave power from shore-based observations are also used to calibrate the relationship. The values obtained are 14 to 94 times lower in magnitude than the accepted relationship for sand beaches, and can be used with greater certainty for other locations in the study area.

Finally, a new method of estimating net transport based on longshore variations in shore morphology over time is developed using data from a 10-year profile survey program. Results suggest that 'slugs' of beach sediment are moved alongshore as collective units, at rates of about 1.4 km.yr^{-1} . Rates of movement are dependent on the prevailing angle of wave approach.

ACKNOWLEDGEMENTS

I would like to thank the following people and organisations for their assistance in the construction of 'My Book'.

My supervisor, Dr. Bob Kirk, for his constructive criticisms of the manuscript and his friendship and guidance over the past five years. He has helped me to achieve far more than a degree and an understanding of the coast.

The staff of Timaru Harbour Board and the South Canterbury Catchment Board, for helpful information. In particular, Mr. Ray Cox and his colleagues (THB) for their days in the surf.

The New Zealand Geographical Society, for financial assistance that is greatly appreciated.

My family, who have given me encouragement, love and support throughout my years thus far. Their tolerance and understanding has been incredible.

My fellow Masters students and other friends within and outside the Geography Department, who have made life far from dull.

Mrs. Glenys Lamb, for her fantastic typing that almost put my proof readers, Mum and Martin (who I also thank), out of a job.

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LIST OF SYMBOLS

A	cross-sectional area of active beach (m^2)
a'	correction factor for the pore space of beach sediment
B_t	foreshore profile volume at time t
\bar{B}_x	mean of measured volumes at a profile ($m^3 \cdot 100m^{-1}$ AMSL)
B_z	standardised profile volume ($m^3 \cdot 100m^{-1}$ AMSL)
C_b	wave velocity at breaking ($m \cdot s^{-1}$)
C_g	group velocity of a wave train ($m \cdot s^{-1}$)
d_b	still water depth at breakpoint (m)
E	wave energy (J)
F	fetch length (km)
g	universal gravitational constant ($=9.81 \text{ m} \cdot s^{-2}$)
H	wave height (m)
H_b	breaker height (m)
I_ℓ	immersed weight transport rate
K	dimensionless constant
K_b	refraction coefficient
k	dimensionless constant = $Q/P_{\ell s}$
ℓ_s	swash length (m)
M	'Material moving force' of wind-generated waves
m	beach surface gradient (vert./horiz.)
P	incident wave power ($N \cdot s^{-1}$)
P_ℓ	longshore component of wave power ($N \cdot s^{-1}$)
$P_{\ell s}$	longshore component of wave power at the breaker zone ($N \cdot s^{-1}$)
Q	volume rate of longshore sediment transport ($m^3 \cdot yr^{-1}$)
S_b	spacing between wave orthogonals at the breakpoint
S_o	spacing between wave orthogonals in deepwater
T	wave period (s)

t	time, or frequency of the wind for a given period (%)
U	mean wind velocity (m.s^{-1})
U_{ℓ}	longshore component of wind velocity (m.s^{-1})
V	longshore water drift speed (m.s^{-1})
V_m	velocity of morphologic translation alongshore (km.yr^{-1})
V_s	average sediment particle velocity alongshore (dist./time)
x, y, z	width, length and depth of active beach (m)
α	angle of wave approach ($^{\circ}$)
α_b	angle of wave approach at breaking ($^{\circ}$)
β	beach surface slope ($^{\circ}$)
ρ	seawater density ($= 1.03 \text{ g.cm}^{-3}$)
ρ_s	sediment density (g.cm^{-3})

CHAPTER 1

LONGSHORE SEDIMENT TRANSPORT IN A

MIXED SAND AND GRAVEL FORESHORE

1.1 LONGSHORE TRANSPORT ON BEACHES

This thesis examines the motions of beach sediment along the mixed sand and gravel foreshore of the South Canterbury coast. The open-coast beach system that will be studied is exposed and subjected through 180° of arc to the energy inputs of the offshore wave environment. Consequently, it is characterised by a movement of the constituent materials in both directions along an axis parallel to the shoreline. This longshore component of movement caused by the interaction of coastal processes is commonly termed 'longshore sediment transport', and it is a major factor in the dynamics of coastal environments.

The most common problem arising in the field of longshore transport research is the calculation and prediction of rates of sediment movement. The magnitude of the longshore movement has major implications for the sediment budget of any beach system, but has, according to Komar (1983), been found to be a very difficult variable to accurately determine. As is the case in many other coastal process studies, the scientific literature that deals with this subject is dominated by work on sand beaches, since these are the most common and economically

important types of beach system to be found in North America and Europe, the global centres of coastal research.

Mixed beaches consisting of coarse-grained material (pebbles and cobbles) in addition to sand present a special case for the study of coastal processes. Long-shore sediment transport has long been recognised as a major factor in the geomorphic development of mixed sand and gravel beaches - Sir John Coode recognised its potential impact on port construction at Timaru, New Zealand, as early as 1875 (Clarke 1921). However, the available methods for calculating rates, many of which are found in the sand beach literature, have not been collectively applied to this type of beach system under a single framework.

Two general problems - the methodology for calculating transport rates, and the application of these to both sand beaches and mixed sand and gravel beaches - can therefore be drawn from this situation. The primary objectives of this thesis are to address both of these problems, by advancing the proposition; 'that the rates of longshore sediment transport on sand beaches and mixed sand and gravel beaches are governed by distinctly different process environments, but can nevertheless be determined by basically similar approaches'.

1.2 PURPOSES OF THE INVESTIGATION

In order to fully understand the purposes of this study, it is necessary to introduce the main reasons why longshore transport rates on beaches are generally

considered so difficult to calculate and predict. A discussion of this state of affairs is, in itself, one purpose of the investigation. Others arising from it however, are of greater importance to scientific research and practical concerns.

The first aspect of the problem is that longshore transport is not a 'process' per se, but only the resulting shore parallel component of a more complex, three-dimensional process régime. Pethick (1984; 88) expresses concern that -

"in almost every case coastal research has tended to treat the landforms as two-dimensional rather than attempt to consider the complexities of the three-dimensional reality. A beach, for example, is seen either as a profile or a plan, an artificial division which...is a necessary expedient in a complicated environment but nevertheless an erroneous one."

Additionally, the superimposition of numerous process elements acting simultaneously to produce longshore movements within the 'three-dimensional reality' complicates the situation even further. "Analysis of the resultant magnitude and direction of currents [produced by these processes] in the nearshore is extremely difficult" (Pethick, 1984; 43).

The second aspect to the problem of rate calculation is that the existing models may not be as widely applicable as they are often assumed to be. Many are developed using only the simplest (and perhaps least frequently occurring) surf zone circulation patterns of a sandy beach. Water circulates within a beach system because the propagation and breaking of waves causes an excess flow of mass and energy into the surfzone, that requires to be balanced by

an outward flow of equal magnitude. It was advanced by Komar and Inman (1970), and is now well established that sandy beaches possess at least three distinctively different kinds of nearshore circulations under different conditions of energy and beach slope. These are pictured in Figure 1.1. In each case, it is known that the circulation pattern is the dominant control of the pattern of sediment movement. The primary factor that determines which kind of circulation occurs is the incidence angle of the wave energy. This term is synonymous with the angle of wave approach, and is conventionally denoted as α . As Figure 1.2 demonstrates, α is the angle between wave crest and shore-line, or between wave orthogonals (rays parallel to the direction of wave movement) and a line normal to the shore.

Under low angles of incidence, the excess flow into the surf zone of a sandy beach is removed seaward by way of a rip cell circulation pattern (Fig. 1.1a). Water flows in both directions alongshore as 'feeder currents' towards the centre line of the cell, from which it then flows seaward in the form of a rip current. This involves a basically two-dimensional flow of water and sand within the system, around a vertical axis. Interactive flow between adjacent rip cells is presumed to be negligible, so is seldom considered. Moderate angles of incidence tend to produce progressive rip cells that are fed from only one direction, and that migrate alongshore with the direction of wave approach (Fig. 1.1b). Longshore transport in this case, may arise from both cell migration and interactive flow, but this most complex circulation state has not been widely investigated. High angles of wave approach

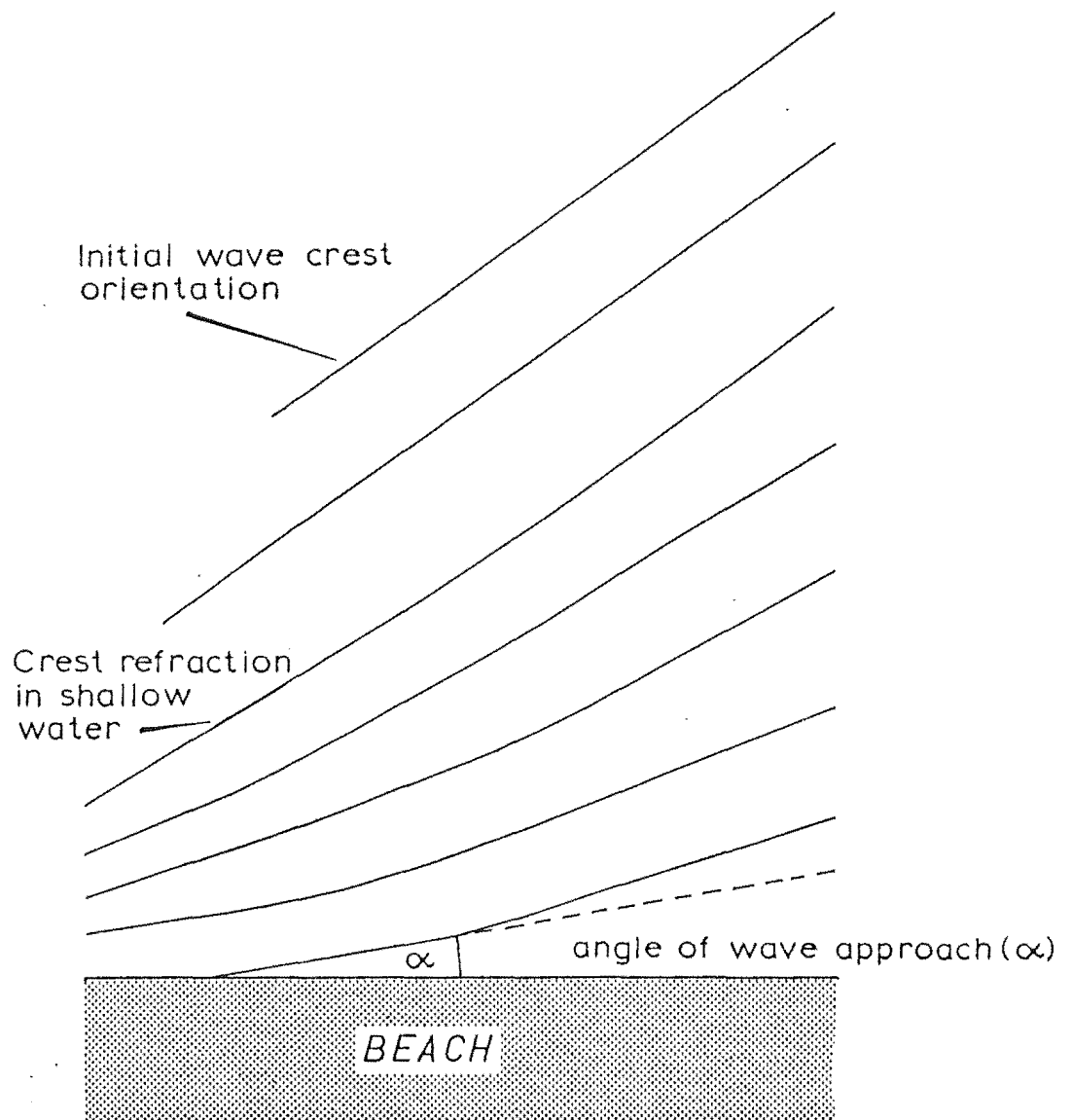


Figure 1.1 The angle of wave approach (α).

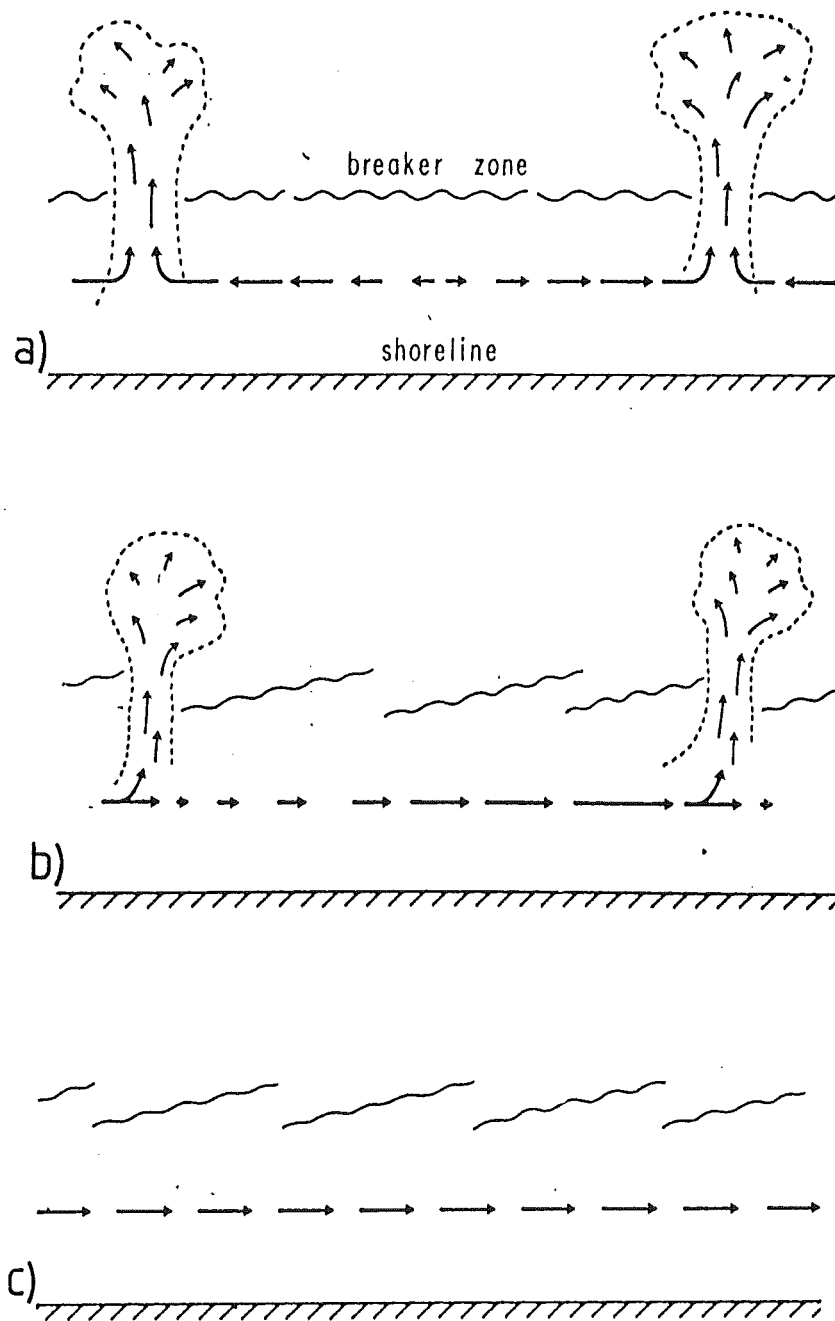


Figure 1.2 Circulation types due to different wave angles on a sandy beach.
 a) Rip cell circulation
 b) Progressive rip cells
 c) 'River of sand'
 (after Komar and Inman, 1970)

produce the simplest surf zone circulation patterns: an essentially one-dimensional flow that transports material as a 'river of sand' along an axis parallel to the shoreline (Fig. 1.1c). Longshore movements are purported to be the most significant component of sediment transfers under this type of circulation.

Because wave refraction, caused by the frictional interference of waves by the sea bed in shallow water, produces angles of incidence that tend toward the perpendicular, the "river of sand" circulation type is often the least likely to occur. For instance, Willyams (1980) noted that, of a wide range of offshore swells received over 56 days at sand beaches in Pegasus Bay, New Zealand, 50% found their final approach perpendicular to the shore: he also observed that circulation currents on these beaches were mainly cellular rips. Svendsen and Jonsson (1976; 36) state also that "a pure longshore current does not constitute a stable system...[and so] seldom - if ever - occurs alone." On account of this, it is an unfortunate fact that the 'river-of-sand' type of circulation is the one most frequently used in the modelling of longshore sediment transport. The other two states are not well represented by most of the models. Additionally, the 'river of sand' characterisation, which was originally proffered by Einstein (1948), has been critically questioned (e.g. by Komar, 1976b) with regard to its oversimplification and general inaccuracy. Thus, it may well be that the existing models of longshore transport are based on an imperfect description of an insufficiently representative beach state.

In a wider context, the applicability of the models has not been tested outside the sand beach situation. There has been little work done on the problem of long-shore transport rates for other kinds of beach, including the mixed sand and gravel systems that Zenkovich (1967;271) asserts have 'the most complicated' dynamics of all beach types.

These beaches demand a thorough understanding, as they are common on the east coast of New Zealand, and present problems of both high scientific interest and economic importance. Consequently, the second purpose of this thesis is to make an initial approach to the problem of longshore transport on mixed sand and gravel beaches by using concepts and methods first developed for the simplest ('river-of-sand') circulation types on sand beaches.

The existing methods for calculating longshore transport rates, that were developed on sand beaches, are of two main types. The first is based on the accumulated knowledge of the ways that coastal processes act on beach materials, and involves sequences of observations and physical reasoning that lead to inferences of relationships between properties and magnitudes of the process inputs, and the rate of longshore transport. The second type is based on the direct measurement of the outcome of the longshore movement of beach sediments, and involves a calculation of the rate of longshore transport that must have occurred to have caused the change from a known previous condition.

These methodological approaches have both been extensively examined but no single method has yet been devised that is known to be a sufficiently accurate measure of the rate of longshore transport on beaches. Komar (1983; 104) suggests that "the standard formulae for predicting [longshore] sand transport rates on beaches could easily be off by a factor of 2, even on beaches with relatively simple configurations." A common procedure used to diminish these errors is to apply two or more methods to the same section of beach, and to make an informed judgement of the "true" rate, based on the results obtained. The maximum obtainable accuracy of the estimated rate on any beach is likely to be related to the number of methods that are able to be used.

With this point in mind, the third purpose of the investigation is to develop and test a new method to approach the problem of longshore transport rates on mixed sand and gravel beaches, in light of the results obtained from the initial approach. This method, which is of the second type mentioned above, will examine changes through time of longshore variations in the volume of the active beach profile. By this means, it is hoped that the inclusion of the four dimensions (length, depth, width and time) will help to eliminate the problem, quoted above from Pethick (1984), of the all too frequent reduction of landforms in coastal research to just two dimensions. If this method can subsequently be shown to also contribute to the solution of practical problems, then a major objective in modern scientific research - to broaden new-found ideas to their wider field of knowledge - will also be accomplished.

In summary, the thesis has four main objectives.

These are

- to assess the previous approaches to the study of foreshore sediment movements and longshore transport rates,
- to describe the process environment in which longshore transport occurs in a mixed sand and gravel beach system,
- to apply several methods for calculating longshore drift rates to sand and gravel beaches,
- to note the implications of the results obtained for the sediment budget of the study area, and for future research in the field of longshore sediment transport.

1.3 FRAMEWORKS FOR ANALYSIS

1.3.1 Theoretical Frameworks

In order to investigate the thesis proposition, it is necessary to establish a theoretical framework, incorporating the process elements and the effects they have on the beach and its materials. So that it can be applied equally well to both sandy and mixed beaches, a special requirement of the framework to be used for this report is that beach structure and composition are considered as variables, and not as constants.

Krumbein (1963) advanced such a process-oriented approach to coastal geomorphology in the form of the Process-Response Model. The framework for this thesis, as set out in Figure 1.3, is based on his model. The process elements of the model are the dynamic factors that control the beach character. These include aspects of the energy

CONCEPTUAL BEACH MODEL

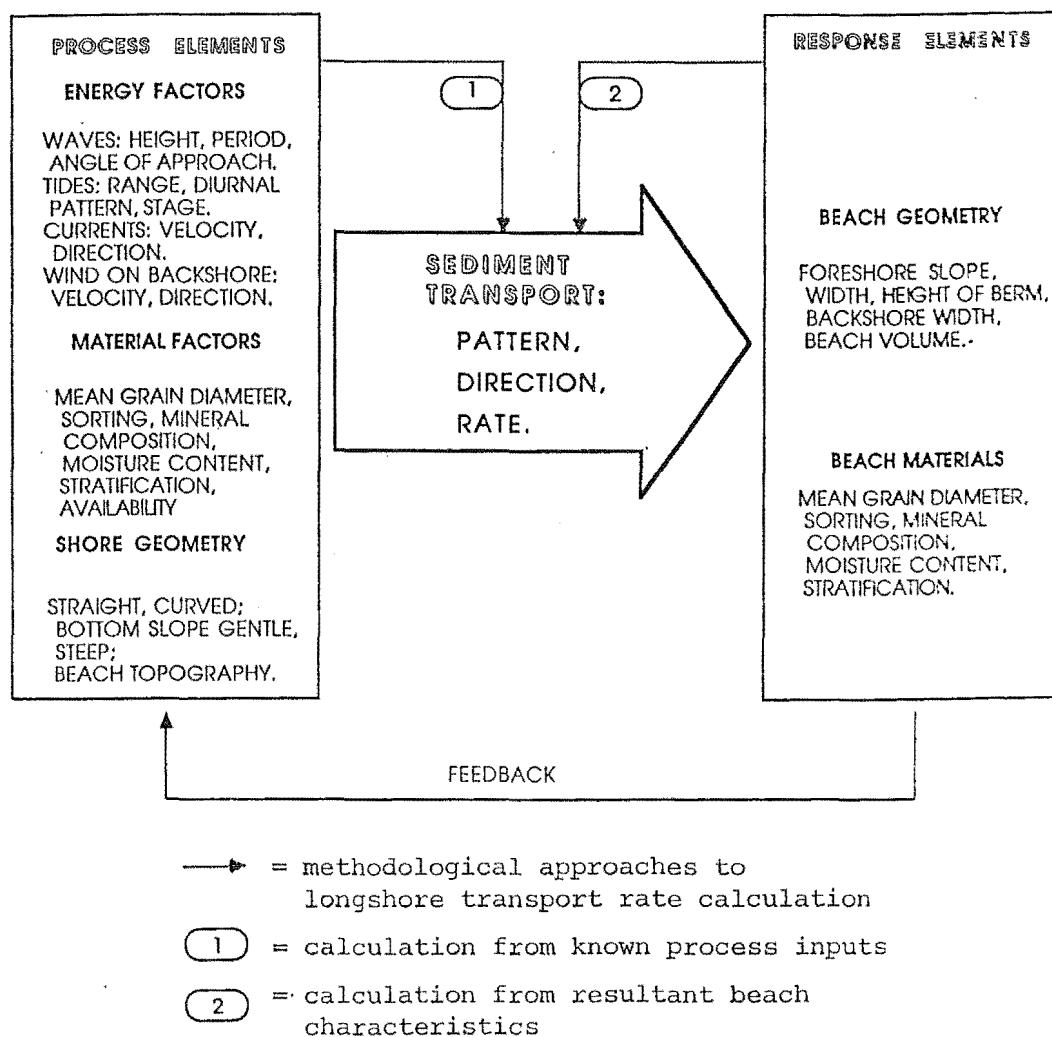


Figure 1.3 Process-Response framework.
(after Krumbein, 1963)

and materials that enter the beach system, and also the geometry of the shoreline. The response elements are the variables that are dependent on the behavioural dynamics of the processes, and include characteristics of the beach form and the materials that the beach is composed of. The conceptual beach model suggests that adjustments take place by way of these mechanisms because the system is constantly striving to attain a state of maximum stability with respect to the process behaviour and beach form.

Longshore sediment transport fits into the framework as one of the mechanisms, implied in Krumbein's original model solely by an arrow, that links process and response. It is a phenomenon that occurs due to the action and interaction of the process elements that are present, and elicits a change in the composition and geometry of the beach by redistributing materials within the system. The Process-Response Model therefore provides an ideal basis for a framework from which to view the processes and patterns of longshore sediment transport.

The two methodological approaches for the calculation of longshore transport rates that were identified in the previous section can be clearly distinguished from the process-response framework. The first approach focuses on the process side of the model, as it involves inferences of longshore transport rates from specified levels of process inputs. This methodology is expressed in Figure 1.3 by the arrow, numbered as '1', pointing from the process elements to the sediment transport mechanisms. The second methodology, numbered as '2' in Figure 1.3, focuses on the response side of the model, since longshore transport rates

are calculated in this approach by measuring the change (degree of response) in the characteristics of the beach that result from the movement of sediments away from their previous locations.

The process-response framework expresses these methodologies in terms of the relationships between processes, responses and sediment transport. It does not, however, accommodate the expression of the variety of pathways of sediment movement into and out of the beach system. A second model must therefore be introduced to complement the framework, and to place the phenomenon of longshore transport into the context of coastal sediment transport in general.

The Sediment Budget Model devised by Miller and Zeigler (1958) expresses this rather different viewpoint for the study of longshore transport, and is reproduced in Figure 1.4. It presents in diagrammatic form, the potential variety of sediment movements into and out of the beach system. Beach materials enter the system from external sources, and leave via the sinks. The model establishes a basis for the quantification of these additions and removals, and so also gives a value for the net gain (accretion) or loss (erosion) of sediment within the beach system.

Longshore transport is shown in the model to be capable of transporting beach materials both into and out of either end of the defined limits of the beach. Consequently, it is often a major component of the sediment budget of open-ended beach systems. Within the context of this model framework, the magnitude (rate) of longshore

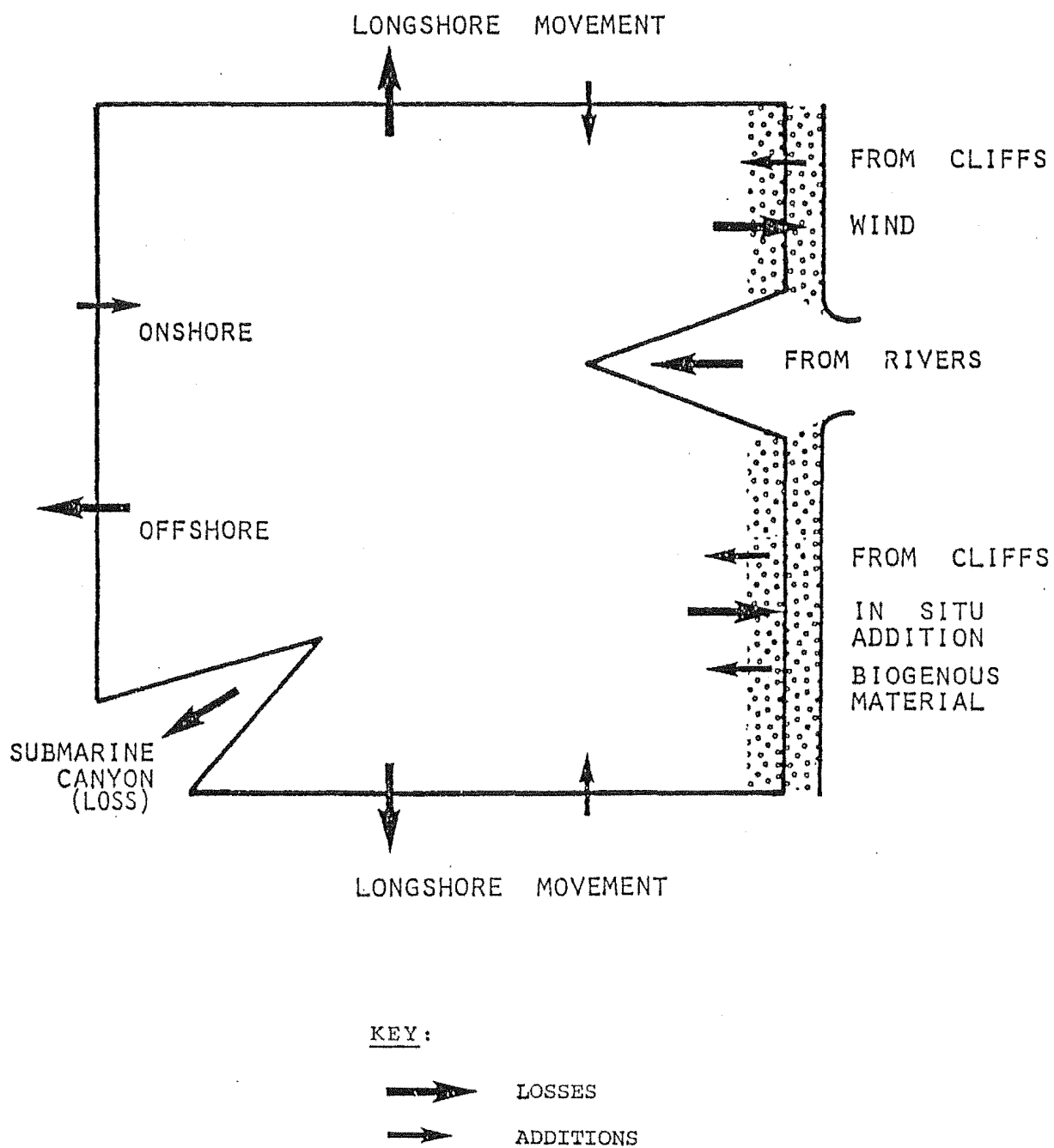


Figure 1.4 The Sediment Budget Model.
 (Source: Siemelink, 1984;
 after Miller and Zeigler, 1958)

sediment transport, and its contribution to the sediment budget, can be more easily determined.

The Sediment Budget Model is especially relevant to the methodological approach that uses the measurement of beach responses to determine longshore transport rates (approach number 2 in Figure 1.3). Accounting for the net change in the amount of material within the beach system, which is the objective of this approach, is precisely the basis of the model. It is appropriate to note however, that this model does not attempt to express the range of internal circulation patterns that can occur within the system. Instead, longshore sediment transport is implicitly regarded as a one-dimensional movement of materials through the beach system, along an axis parallel to the shoreline. Here is one instance of a conceptual beach model that expresses longshore transport solely from the "river of sand" viewpoint.

1.3.2 The Foreshore Zone

The beach foreshore is the coastal zone on which the thesis research is concentrated. It is defined here as the section of a beach from the breaker zone (where incident waves break on approaching shallow water) to the swash limit (where broken waves reach their maximum shoreward distance). Between these two limits is an interface between land, sea and air that buffers the hinterland behind the beach from the power of the incoming ocean waves. Pethick (1984; 15) states that "the energy of a wave exists in two forms; potential, due to the deformation of the wave above still water level; and kinetic, due to the orbital movement of the

water particles within the wave form." As in the 'river of sand' models, some component of this may act alongshore where waves approach the shore at an oblique angle. It is within the foreshore zone that the remaining component of wave energy flowing at right angles into the shore is completely eliminated. Some of it is reflected off the foreshore face and returns seaward without altering the face in any way. A significant portion, however, is dissipated within the foreshore zone by conversions to different forms and directions of energy flows. The most significant foreshore energy conversion, in the context of this thesis, is from the potential and kinetic energy of waves, to mass transport (the kinetic energy of water and solid materials) alongshore.

Although the dissipation and reflection of wave energy is a function common to all beaches, the morphologies and dynamics of beach foreshores are highly variable. These depend primarily on the characteristics of the wave energy and sediments that are supplied to the system, as suggested by the model framework that was presented in Figure 1.3. However, the long-term energy and sediment supplies to any particular beach tend to remain relatively constant in terms of the process factors listed in Figure 1.3, fluctuating within measurable limits. Consequently, coastal geomorphologists have been able to categorise beach foreshores in terms of their wave climates and material compositions, and regard each type as having distinctive process environments.

Open-coast, mixed sand and gravel foreshores, which are the focus of this thesis, differ from open-coast sandy

foreshores primarily in terms of their material composition. 'Sand' and 'gravel' are accepted terms used to describe mineral particles that have median (b-axis) diameters below and above 2 mm, respectively. The beach type in question comprises significant components of both size classes, whereas sand beaches are composed almost entirely of sand-sized sediments. Secondly, these two types of beach foreshore differ greatly in terms of their morphologic and dynamic features.

The 'classic' sandy foreshore pictured (in profile) in Figure 1.5a has a wide, gently sloping face over which the incident wave energy can be dissipated. It is conventionally divided into the breaker zone, the surf zone and the swash zone. The surf zone is the region in which broken waves reform while advancing landward. It is the widest of the three zones and is often considered to be the most important with regard to the longshore transport of sand (e.g. Basco, 1986; U.S. Army, 1984). Turbulent surf zone currents transport sand in suspension and as bedload, in the patterns of circulation described earlier.

Mixed sand and gravel foreshores possess the characteristic features shown in Figure 1.5b. The sediments are not truly mixed, but are sorted by wave action into zones within the beach, according to their particle shape characteristics. Incident waves break on reaching the nearshore step, and rush up the beach as swash, returning as backwash. The surf zone is less than a few metres wide, and is often virtually non-existent. Consequently, longshore transport on mixed beaches is claimed to be greatest in the swash zone, particularly in the uprush phase (Zenkovich, 1967; Muir Wood, 1970; Kirk 1980).

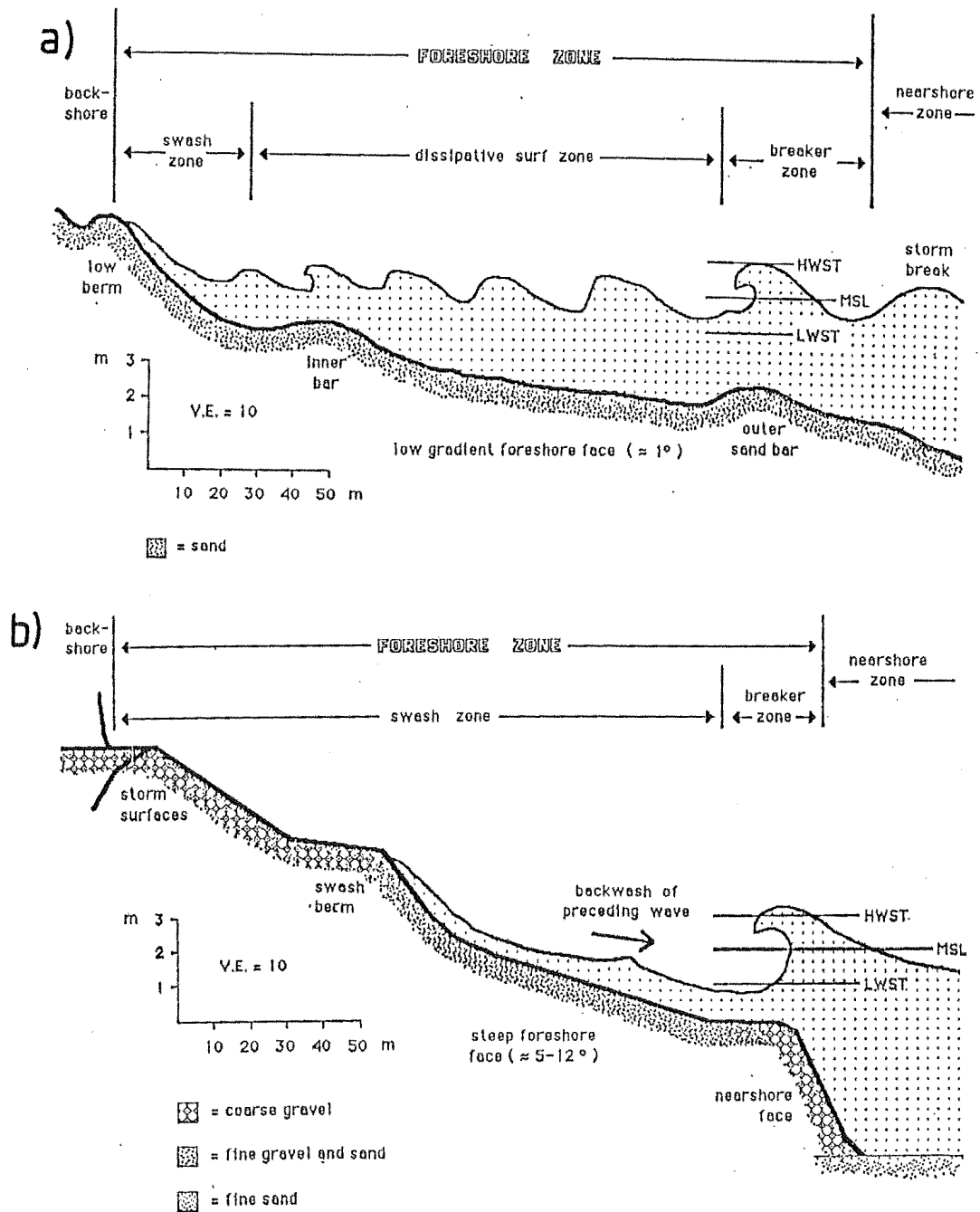


Figure 1.5 Typical cross sectional profiles of open-coast foreshores.
 a) Sand beach (after Wright et al, 1979)
 b) Mixed sand and gravel beach (after Kirk, 1980).

These clear differences between sand and mixed-sediment foreshores indicate that the patterns and processes of the longshore movements of beach materials are also very different. This thesis aims to show that despite these dissimilarities, the calculation of longshore transport rates can be initially approached in the same way for both types of beach.

1.4 THESIS STRUCTURE

An important problem in the science of coastal geomorphology, and a framework for the investigation of this problem, have been identified.

The rest of this thesis works towards fulfilling the objectives, with the intention of developing and testing a new method for solving the problem of longshore transport rates, based on the changes of longshore variations in shore morphology over time.

The following chapter; 'Longshore transport rates - an old problem', discusses previous approaches to the problem, and specifies their inherent sources of error. Chapter 3; 'Sand and Gravel Beaches - a new situation', describes the study area in some detail, identifying in particular the action of hydraulic forces and their effects on foreshore sediment transport. Previous estimates of longshore transport rates in the region are also reviewed.

An initial understanding of the mechanics of longshore transport is considered essential for the development and comprehension of rate calculations. The causes and nature of the longshore component of water and sediment

movement are therefore examined in Chapter 4; 'Processes and Patterns of Longshore Motion'. This is followed by the application of previous approaches for calculating rates to mixed sand and gravel beaches in Chapter 5. On the basis of the preceding chapters, a new approach to the calculation of transport rates is developed, tested and evaluated in Chapter 6.

The thesis concludes with a summary of the major findings gained from the research, and suggestions that may aid future progress in the field of longshore transport research on beaches.

CHAPTER 2

LONGSHORE TRANSPORT RATES - AN OLD PROBLEM

2.1 INTRODUCTION

The occurrence and magnitude of the movement of beach sediments alongshore has long been a subject of considerable interest and concern in the field of coastal geography. In the early nineteenth century, the continual motion of pebbles by the action of the sea on shingle beaches, and their ultimate progression in a dominant direction alongshore, were "facts well known and commonly observed" (Palmer 1834:567). Early studies of longshore transport on beaches (e.g. Palmer, 1834; Johnson 1919) were mostly observations and descriptions of the patterns of particle movement, and of the general effects on the accretion and erosion of coasts. As quantitative geographical principles grew through the twentieth century, so too did the desire to measure these coastal phenomena. This chapter examines past attempts to evaluate longshore sediment transport on beaches, and assesses the success or otherwise of the methods used.

2.2 THE NEED FOR RATE ESTIMATES

In accordance with the Sediment Budget Model presented in Figure 1.4, the rates at which materials enter and leave a beach system totally control the net gain or loss of sediment volume. Thus, the rate of beach gradation

(erosion or accretion) is proportional to the difference between the inputs and outputs of sediment. The major role of longshore sediment transport in the balancing of inputs and outputs of open-ended beach systems lays a great importance on the need for some knowledge of the rate at which the transport occurs.

It is the large-scale beach changes that can result from longshore transport that draw the attention of those concerned with coastal management. Much of the concern deriving from the phenomenon of longshore transport has occurred through adverse interference with drift at man-made coastal structures (e.g. harbours and settlements); and by excessive introductions to, or removals from, the sediment budget of adjacent coasts, resulting in unwanted levels of accumulation or erosion. "The trouble of travelling shingle and sand [parallel to the shore] is one that is met with in many parts of the world and has engaged the attention and skill of many eminent engineers [and geographers!] on many occasions with varying results" (Clarke, 1921:61). As a prerequisite to overcoming the problems of coastal change, it has often been found necessary to acquire an understanding of the conditions of longshore transport that facilitate the changes. Zenkovich (1967) was of this opinion when he wrote:

"Study of the processes that alter the appearance of the coastline begins with the displacement of beach material along the shore" (p.317).

Consequently, an appreciation of the rate of longshore transport is of primary importance to the management of the coast and its associated man-made structures.

2.3 APPROACHES TO THE PROBLEM

The widespread need for estimates of the rate of longshore sediment transport has demanded the development of a sound methodological base. Early attempts to quantify the rate of longshore transport were usually based on measurements of beach changes near coastal structures. An example from 1895 cited by Clarke (1921:61; original source not stated) estimated the rate of sediment accumulation caused by the construction of a harbour at Timaru, New Zealand. Clarke implicitly assumed the resulting coastal change was due entirely to longshore transport. This was typical of the early approaches, insomuch as the attention was focussed more on the magnitude of beach response than on the rate and role of longshore movement that caused it.

Since the 1950's, when technology, and the need for a greater knowledge of coasts began to flourish, it has become more widely acknowledged that the rate of longshore transport can be deduced by alternative means or from study at other locations, and the results subsequently applied to the relevant situation. As a result, an admirably diverse range of methods has been advanced by coastal scientists in order to approach the problem. The first decision that therefore has to be made when determining the longshore transport rate at an identified site, is the method to be used. Few of the many methods that have been developed can be applied to all situations, since they make specific assumptions that cannot always be reasonably justified, and demands on the required data that often cannot be met. The best method to use is the one that most closely fits the data and situation being studied.

It was proposed in the previous chapter that the existing methods for calculating longshore sediment transport rates are of two main types. The first views longshore transport as a product of the interaction of coastal processes, whereas the second views it as a cause of beach responses. Historically, the second type was the first to be developed to any extent, but the Process-Response framework of this thesis explains the logic of the order in which they will be reviewed here.

2.3.1 Potential Transport Rates

The movement of sediment alongshore is reliant on the action of process factors within the beach system. Similarly, the rate of longshore transport may be assumed to depend on the characteristics, and especially the magnitudes, of the relevant processes. If these assumptions are valid, then any given magnitude of a combination of process factors must have the potential to produce a proportional level of sediment movement in a direction parallel to the shoreline. As a result, it has become evident that the potential rate of longshore transport for any process environment can be estimated from information about the governing processes. This approach has developed a broad methodological base over the past five decades.

A common feature of the 'potential rate' approach is the determination, from a suitable data base, of a mathematical statement that expresses the rate of longshore movement of mass or energy as a function of several, or less frequently only one, independent process variables. By this means, a predictive estimate of the flow rate may

be made from a knowledge of the environmental factors that cause it.

It is asserted in the Shore Protection Manual (U.S. Army, 1984; 4.27) that "waves arriving at the shore are the primary cause of sediment transport in the littoral [nearshore] zone." This fact has been widely recognised by coastal geographers since at least the nineteenth century. Cornaglia (1889) began his acclaimed paper, 'On Beaches', with an equally strong statement to that effect, and others before him have expressed the same view (e.g. Palmer, 1834). However, it was only in 1936 that a notion was put forward, by Munch-Petersen (in Dept. Army., Corps Eng. 1950) that "there must be a relation between wave energy and material movement along the coast." More precisely, the direction of longshore sediment transport must be the same as that of the dominant wave approach relative to the shoreline, and the rate must be related to the level of wave energy. The problem, therefore, is to establish a formula defining the energy and direction of waves, and from this the transportation ability of the waves can be determined.

Longshore wave energy generated by winds

Early attempts to calculate the energy of offshore waves were based on the environmental factors that were known to control wave formation. The dominant type of ocean wave^s are wind waves, which are generated by winds blowing over water surfaces. The form, and therefore the energy flow, of wind waves approaching the shore has been shown to be determined by the fetch (the effective distance the wind has blown over the sea), the speed, duration and direction of the generating wind, and the decay distance

(the distance the wave has travelled away from the generating area), (Davies, 1972). These parameters have been incorporated into equations for estimating the ensuing wave conditions and so also for predicting the potential longshore drift rate produced by the waves.

Typical of this method is the contribution of Knaps (1938, in Zenkovich, 1967) who improved the original formula for evaluating the shore parallel 'material moving force' (M) that was devised by Munch-Peterson in 1936. Knaps' equation (with altered notation) is:

$$M = KU^3 t \sqrt[3]{F} \sin \alpha \cos \alpha \quad \dots 2.1$$

where U is the mean wind velocity (m.s^{-1}),

t is the relative frequency (duration)

of the wind for a given period (%),

F is the fetch length (km),

α is the angle between the coastline and

the direction of wave propagation (degrees)

and K is a coefficient of unstated magnitude

The units of the force M are not stated, and the coefficient K is assumed for simplicity to be a constant, but was acknowledged by Munch-Peterson to vary in relation to other factors (Zenkovich, 1967). The formula is therefore intended less for absolute calculations of sediment transport, than for an indication of the relationships of wind parameters to the transport of beach materials by waves.

Wave Energy Flux Method

Advancements in the collection of wave data have opened the way for new methods of analysis that were not

possible in earlier times. In particular, coastal environments can now be more accurately described in terms of the wave climate (which describes the total range of combinations of wave parameters that occur in a region). This in turn, allows comparisons of properties of the wave climate with several aspects (such as sediment transport) of the coast to which it imparts its energy. Instruments and methods have been developed since the 1950's that can measure some wave parameters with an accuracy that is sufficient for detailed analyses.

Wave parameters have been used to mathematically express the flow of wave energy and its longshore component, in a theoretical approach to sediment transport that is commonly referred to as the 'Energy Flux Method' (e.g. Galvin and Schweppe, 1980) or the 'Wave Power Approach' (e.g. Komar, 1976).

It is assumed in this approach that the work done by the waves in moving sediment alongshore is related to the longshore component of wave energy flow. The rates at which wave energy (E) is transmitted or work is done through a vertical plane perpendicular to the direction of wave advance are expressed as the wave energy flux (EC_g) or as the wave power (P). When a wave field approaches a coastline, only the longshore component of the wave power (P_ℓ) works directly to move sediments along the coast. This component is defined by Figure 2.1. P_ℓ is dependent on the energy (mass and velocity) of the wave form, and on the angle of wave approach. From physical considerations, it has been determined that (U.S. Army, 1984):

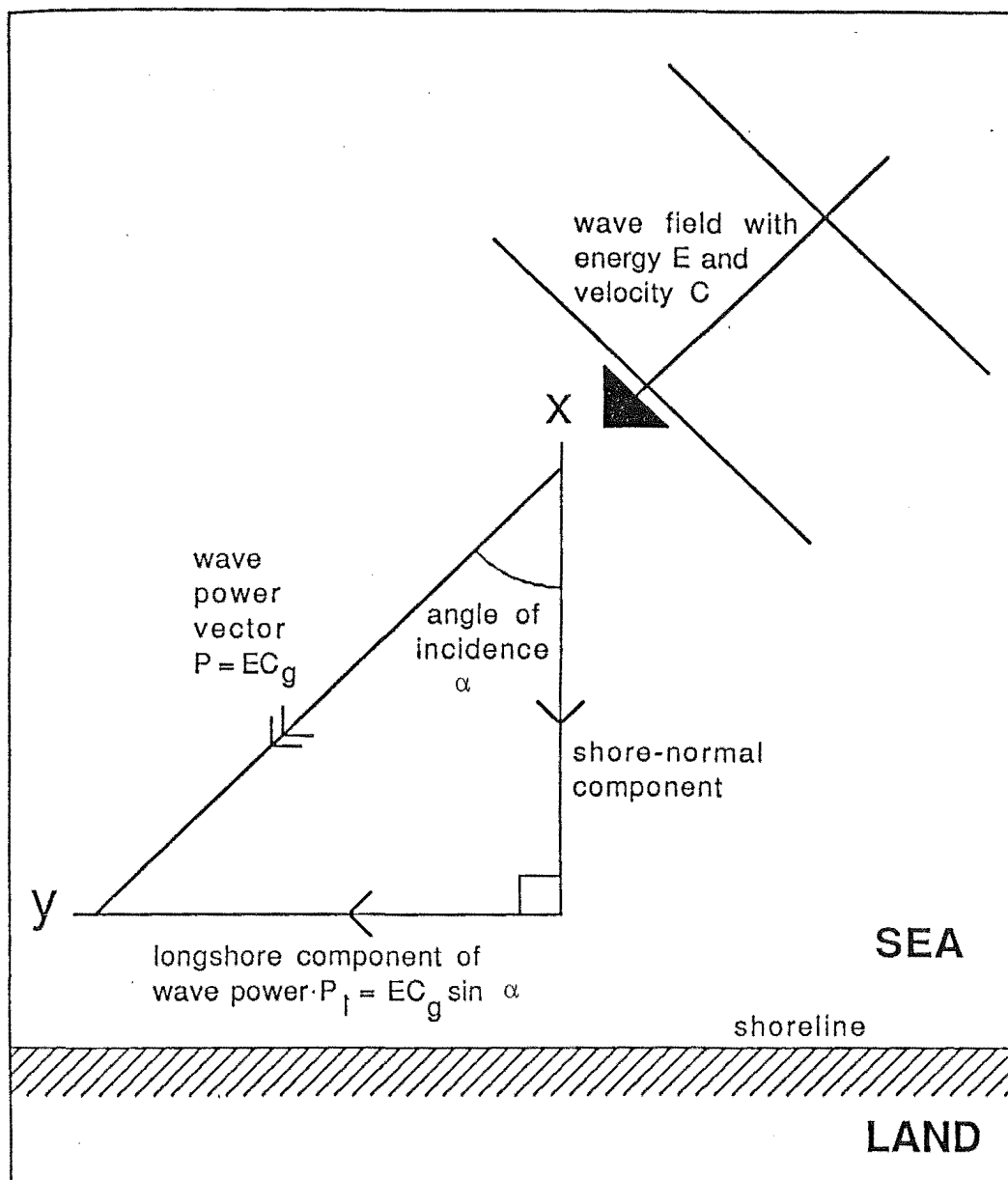


Figure 2.1 Wave power relationships at a coastline. Plan view.

$$P_{\ell} = \frac{\rho g}{8} H^2 C_g \sin \alpha \quad (\text{Newtons.s}^{-1}) \quad \dots (2.2)$$

where ρ is the seawater density ($= 1.03 \text{ g.cm}^{-3}$),

g is the universal gravitational constant

($= 9.81 \text{ m.s}^{-2}$),

H is the wave height (m),

C_g is the group velocity of a wave train

(m.sec^{-1}),

and α is the angle of wave approach (degrees).

The wave energy flux changes as the wave field approaches the foreshore. Frictional interference by the sea bed in shallow water alters the nature of the wave field by 'shoaling' (transforming) and 'refracting' (redirecting) the waves. Only the wave period remains constant, while the velocity, length and angle of approach (usually) progressively decrease, and the height increases. Consequently, the longshore component of wave power supplied to the foreshore zone is best approximated by the longshore energy flux at its seaward boundary (i.e. the breaker zone).

The group velocity at breaking is approximated by the phase (individual wave) velocity C_b for which

$$C_b = \sqrt{g (d_b + H_b)} \quad \text{m.s}^{-1} \quad \dots \quad 2.3$$

where the subscript b refers to breaker zone conditions. The still water depth at which a wave breaks (d_b) is dependent on the beach slope (m) and the height (H_b) and period (T) of the wave, as shown by Figure 2.2.

Figure 2.3 shows how an oblique wave approach disperses the energy over a length of shoreline that is equal to $1/\cos \alpha$. Since it is the level of energy at any point along the beach that is relevant to the transportation

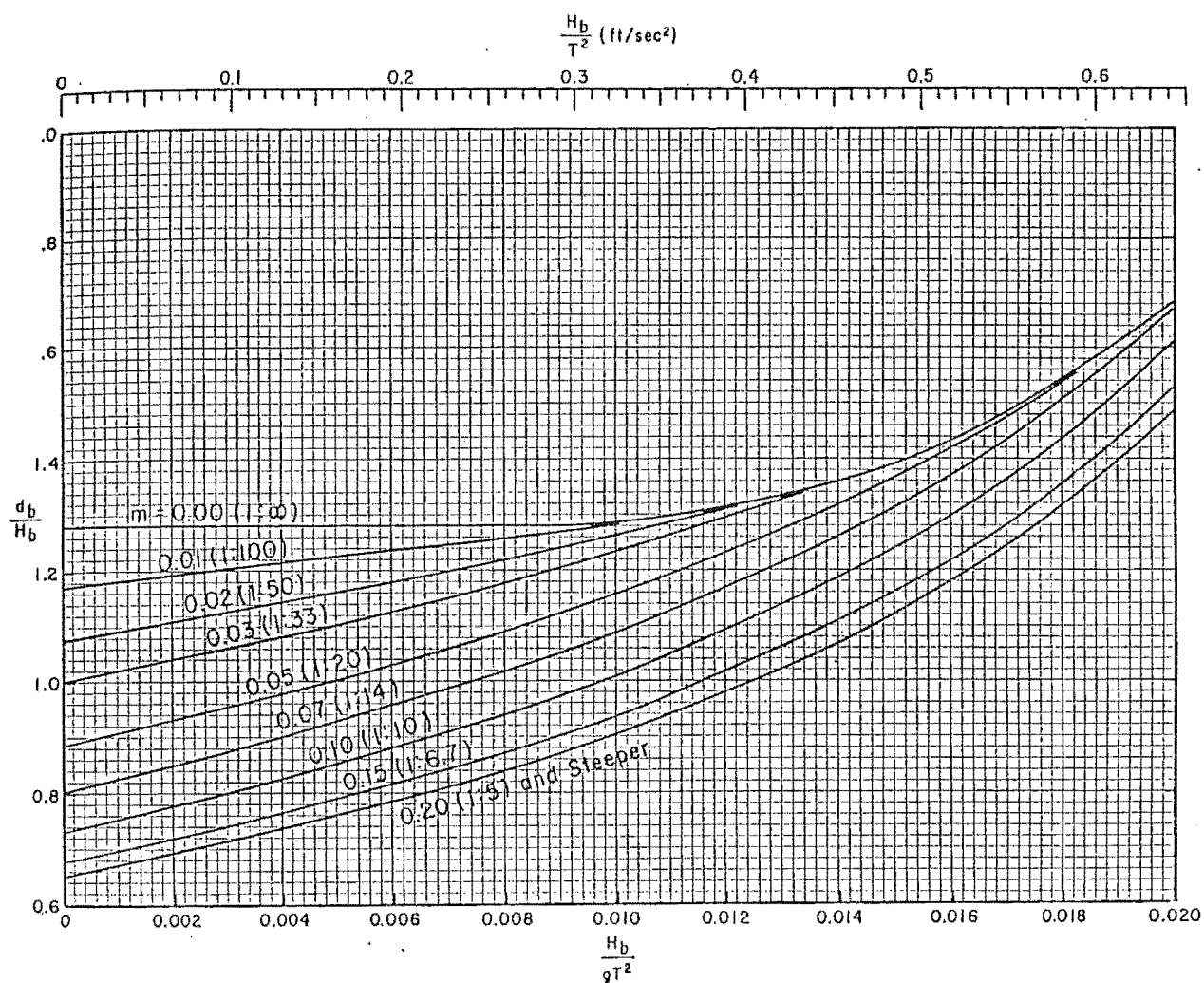


Figure 2.2 Dimensionless depth at breaking (d_b/H_b) versus breaker steepness (H_b/T^2).

Source: U.S. Army, 1984

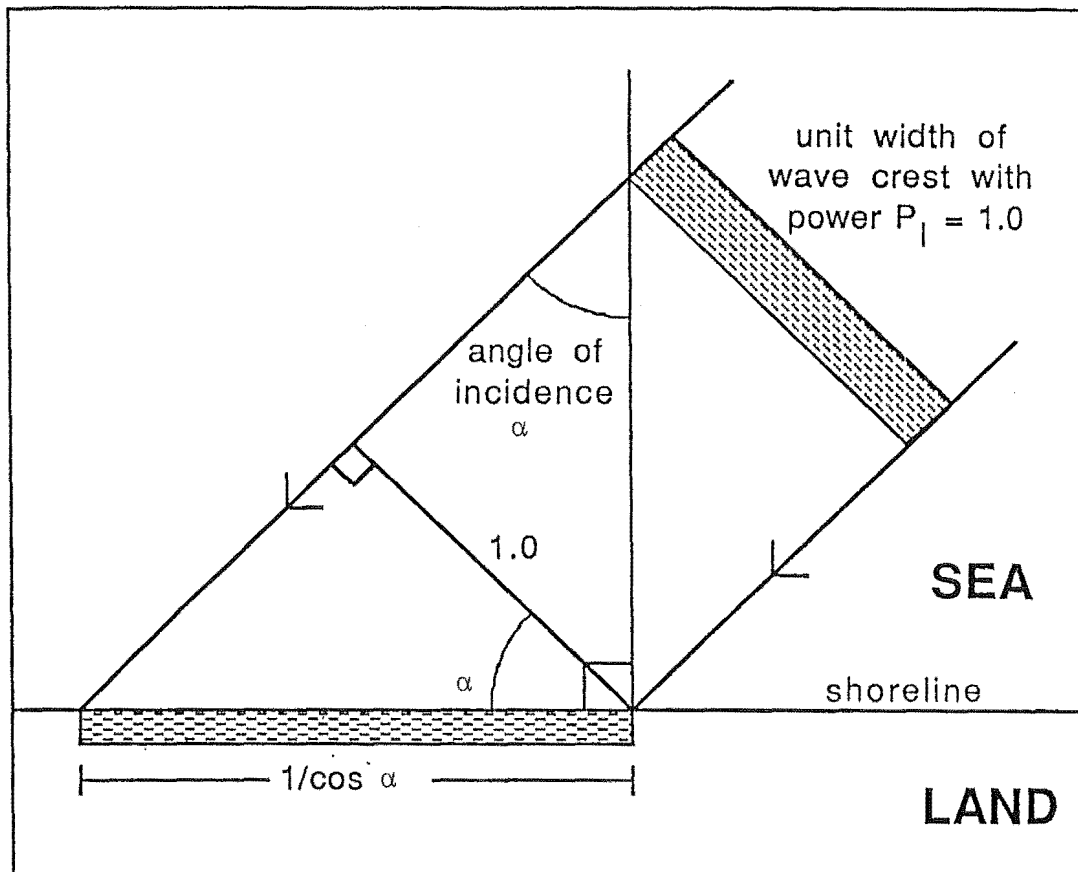


Figure 2.3 The dispersion of wave energy at a shoreline.

of sedimentary particles, this dispersal affects the rate of sediment transport. Therefore, the longshore component of wave power entering the foreshore zone, per unit length of beach front, can be approximated by

$$P_{\ell s} = \frac{\rho g}{8} H_b^2 \sqrt{g (d_b + H_b)} \sin \alpha_b \cos \alpha_b \dots (N.s^{-1}) \dots 2.4$$

which simplifies to

$$P_{\ell s} = \frac{\rho g}{16} H_b^2 \sqrt{g (d_b + H_b)} \sin 2\alpha_b \dots (N.s^{-1}) \dots 2.5$$

(U.S. Army, 1984)

Other approximations of $P_{\ell s}$ that are based on different assumptions and use deepwater wave parameters, are not equivalent, but are reported by Galvin and Schweppe (1980) to give values that agree within a factor of 2. The subscript 's' is a conventional notation meaning 'surfzone', that is used in this equation (for example, by Komar, 1976a; U.S. Army, 1984; Pethick, 1984). Its widespread use is probably to emphasise that the dissipation and sediment-moving ability of the wave power entering the foreshore usually predominates in that zone. It should be noted though, that under certain conditions the swash and breaker zones are the dominant regions of foreshore sediment transport.

The final step in the Energy Flux Method for estimating longshore transport rates is to define the relationship between the longshore component of wave power in the foreshore ($P_{\ell s}$) and the rate of sediment transport (Q). In a review of the available data, Inman and Bagnold (1963) proposed that the relationship is positive and linear, and so is represented by the equation:

$$Q = kP_{\ell S} \quad \dots \text{(various units)} \quad \dots 2.6$$

The coefficient k is assumed to be a positive constant, but its precise value has been disputed in the past. Estimates of k have been made by comparing calculated values of $P_{\ell S}$ with the levels of sediment transport measured for the same situations by other methods. For sand beaches, these have ranged from 4000 (after Inman and Bagnold, 1963) to 7500 (U.S. Army, 1984), for values of Q in cubic yards per year, and $P_{\ell S}$ in foot pounds per second per foot of beach front. The latter of these works concedes that the average residual of the available data is at least 28% of the value of prediction, while Komar (1983) suggests that these standard formulae could easily be out by a factor of two, even in relatively simple cases.

Internal parameters

Because the processes operating within the foreshore zone are recognised as being the most important direct control on longshore sediment transport in beach systems, internal parameters have been incorporated into empirical equations for Q in an attempt to increase the accuracy of predictions. These are parameters that are determined by the interactions within the foreshore of the externally-controlled parameters of air, water, and sediment. The most important of these to longshore drift rates include, according to Basco (1982), the beach width and slope, swash dimensions, the depth of disturbance of the beach face by the motion of water, the sorting of sediment across the profile, and the velocity of the longshore current.

The use of internal parameters in this way strengthens the 'potential rate' methodology by providing "a more fundamental examination of the processes of longshore transport" (Komar 1976b; 51).

2.3.2 Transport Rates from Beach Responses

Longshore movements of beach materials necessarily produce a sedimentological response which usually manifests itself as a change in the morphology and material composition of the beach. The nature of the response, and especially its magnitude, are frequently difficult to discern from the complex interactions of the coastal environment. Nevertheless, in a few situations where the response is both discernible and measurable, methods have been developed to estimate the rate of longshore transport from the magnitude of the beach response.

Morphologic responses

The net direction of longshore sediment transport is often apparent in the shore parallel asymmetry of coastal landforms that results from unequal rates of sediment transport into, along and out of the beach system. Figure 2.4 shows how an impedance of sediment flux at either end of the system affects the sediment budget, and alters the symmetry of the updrift and downdrift sections. Such a condition can arise in a number of situations.

Artificial projections extending into the coastal environment (groynes, breakwaters, moles, etc.) often impede the longshore transfer of beach material in this way, and so cause progradation of the beach updrift of

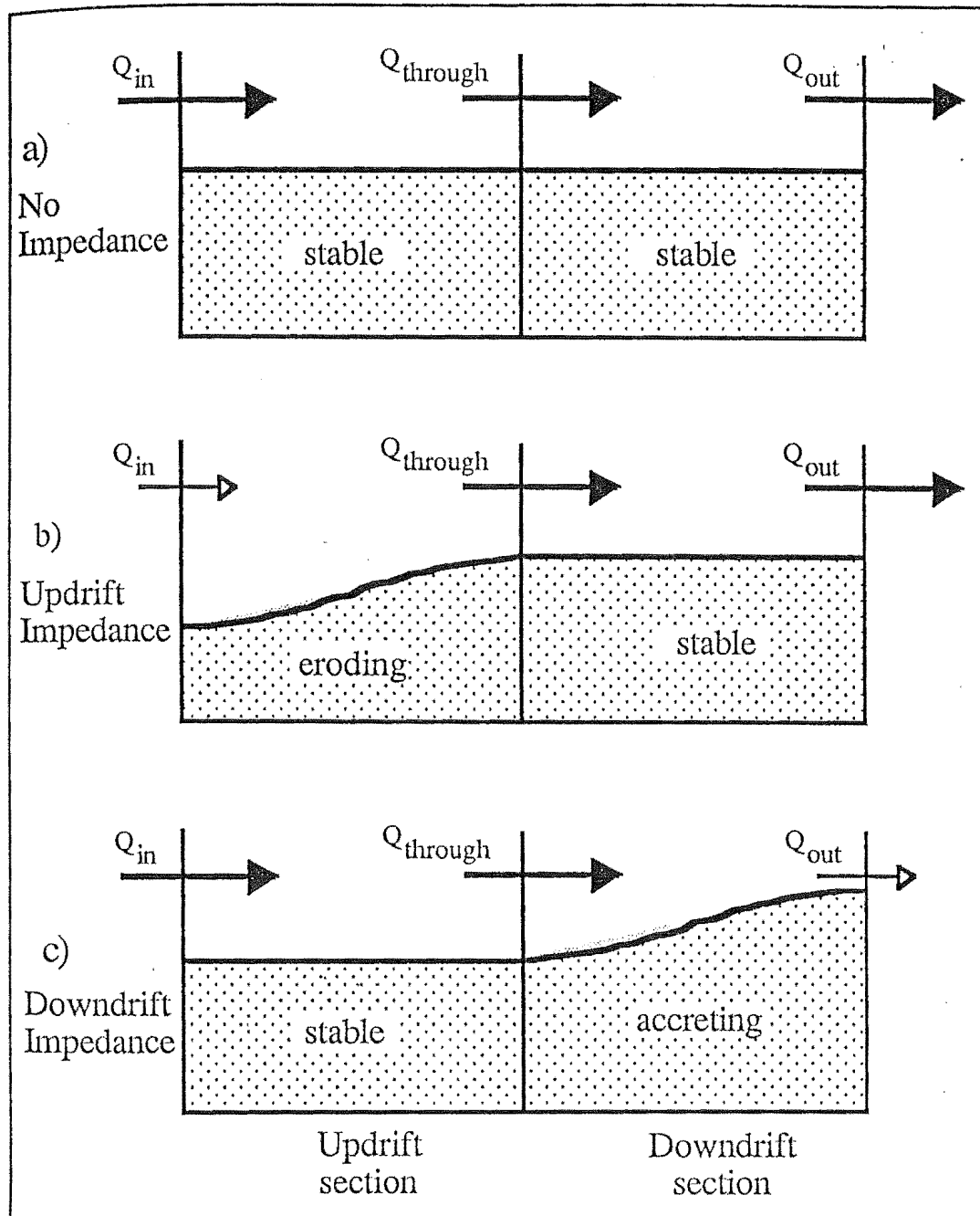


Figure 2.4 Morphological asymmetries caused by an impedance of sediment flow.

the structure, while the opposite side experiences erosion. The changes in beach volume caused by the movement of foreshore sediments near such 'littoral barriers' are shown in Figure 2.5 to equal the plan area of the beach change multiplied by the vertical height range of the foreshore zone. The rate at which this change occurs can represent the net longshore transport rate, provided that three major assumptions are satisfied (Greer & Madsen, 1978). Firstly, the littoral barrier must be 100% effective in preventing the transfer of sediment. Secondly, no sediment transfers must occur through the seaward foreshore boundary. Thirdly, the longshore sediment transport through the updrift and downdrift boundaries must be unaffected by the presence of the littoral barrier.

Natural geomorphic features may also impede littoral drift, and so indicate the direction of transport in a similar manner. Jacobsen and Schwartz (1981) suggest that the downdrift orientation of the axes of coastal spits is 'one of the most reliable indicators of net shore-drift direction'. They also note that the diversion of the mouths of large rivers 'always appears to be in the direction of net shore drift'. These landforms are often inefficient or non-permanent sediment traps, so unfortunately they cannot be used to accurately calculate drift rates.

A final morphologic indicator of the direction of longshore drift is the migration of 'sinuous curves and bulges' (Dolan, 1971) that have been observed on many 'straight' open-coast beaches (Handin and Ludwick, 1950;

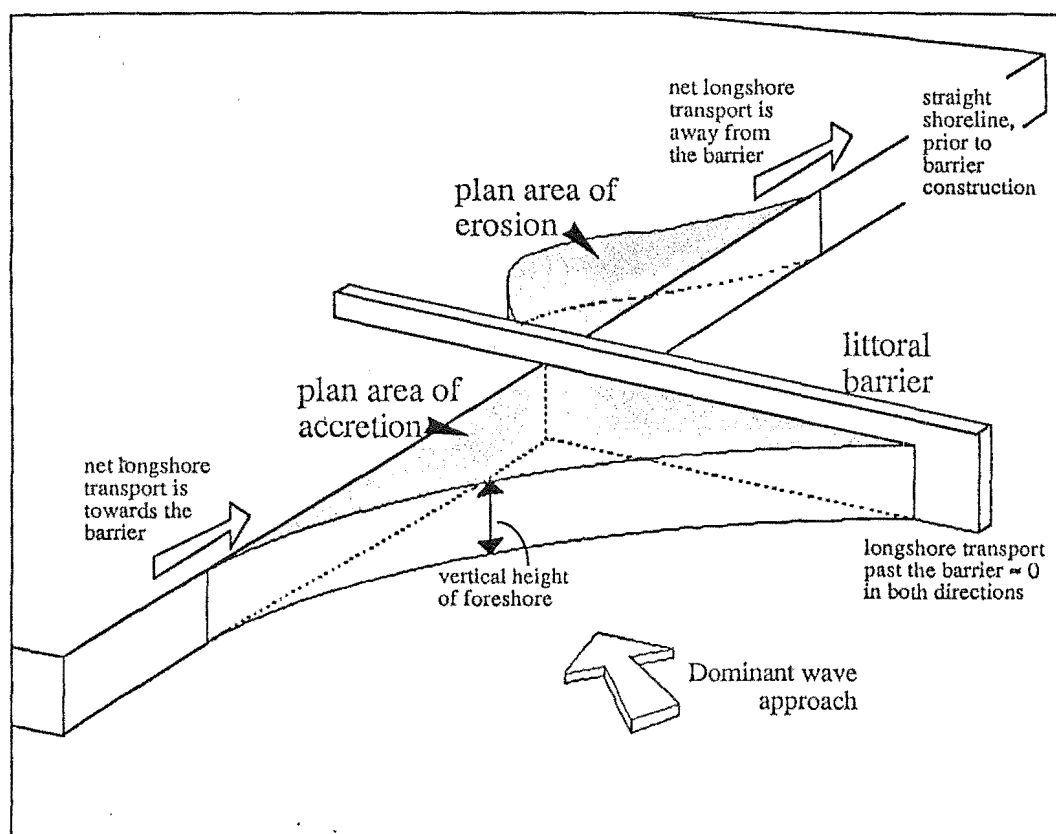


Figure 2.5 Beach volume changes at a littoral barrier.

Komar, 1976). Sonu (1969) notes that these appear to move as a collective unit in the direction of wave propagation. Their rate of migration may also give some indication of the longshore drift rate of the beach material from which they are formed. This phenomenon will be the subject of detailed study later in the thesis.

Material responses

Sediment tends to migrate along a coast in the direction of the dominant drift. Thus, a non-uniform dispersion of beach materials from an identifiable sediment source often provides evidence of the net littoral drift direction. Figure 2.6 shows how coastal processes alter an injected mass of material as it moves alongshore, away from the source.

In a few cases where the source material is easily distinguishable from other beach sediments, material responses can be used to measure the rate of longshore transport. These identifiable materials are known as tracers, and they come from both natural (e.g. rivers, cliffs) and artificial (e.g. dredge dumpings) sources. If the precise time of input of the tracer is known, and also the distance of the material away from the source after an elapsed time, then the average particle velocity that is required for the measured response to occur can be easily calculated.

The input of tracers can be simulated by injecting a mass of 'non-native' or artificially marked materials on to a beach. They may then be recovered after a period of exposure to the processes that cause longshore sediment

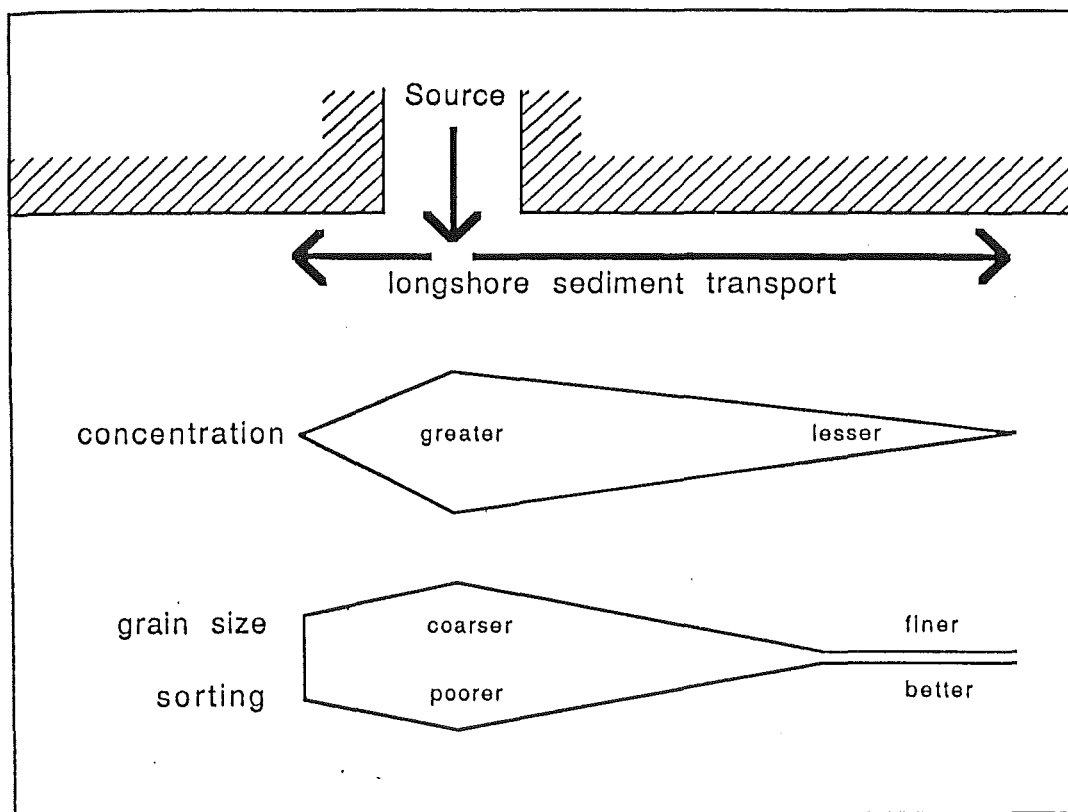


Figure 2.6 Material responses to longshore transport.

transport. By this means, the duration of exposure is controlled, and the distance that the material moves alongshore can be measured, to give an indication of the rate of longshore transport. Galvin (1964), Hails (1974) and others have described the widespread use of the tracer method by coastal scientists. The sediment to be used in the experiment can be artificially tagged using paints (Caldwell, 1983), fluorescent dyes (Ingle, 1966), or radioactive substances (Duane, 1970), or can comprise materials not otherwise found in the study area (Wright et al, 1978; Hattori & Suzuki, 1978). Surprisingly large injections of tracer are often deemed necessary in order to maintain a reasonable level of recovery in view of high losses from the sampling area. Ingle (1966) suggests that 3-40 pounds (1.5 - 20 kg) is a reasonable amount, but masses of over 400 kilograms have been used for longer term studies (Hastie, 1983). The tracer is usually recovered by systematically searching or sampling the beach face near (mostly down-drift of) the injection site. The distribution of tracer recovery alongshore is then determined, and from this the rate of drift can be calculated. However, Greer and Madsen (1978) emphasise the view that several basic assumptions of the tracer method are often violated, and Johnson (1965; 549) expressed an opinion that "other procedures for establishing direction [and rate] of drift...probably would in most instances be more preferable than the use of artificial tracers."

2.4 THE EXPRESSION OF RATES

Depending on the nature of the method used, and the purpose of the results obtained, the estimated rate of longshore transport can be expressed in a variety of different forms. Each form is generally able to be related to others by simple means, but it is important to know which form is being used in any investigation, as correct interpretations of results depend on it.

The most important variety of expression distinguishes between gross transport and net transport. Variable angles of wave approach at a coastline bring about two directional components of sediment transport alongshore; one to the 'right' and the other to the 'left'. The gross longshore transport rate is a measure of the total movement of beach materials, and is equal to the sum of the two components transported past a line across the beach, in a given time period. The net rate describes the resulting movement in one direction that derives from an imbalance of the two components, so is equal to the difference between them. The net rate is usually the most useful form of expression, since it is the one that usually controls beach responses.

The time period over which the longshore transport is measured can have a major effect on the magnitude of the rate estimate. Because the coastal environment is subjected to a plethora of rhythmic and irregular changes over time, the rate of longshore transport is similarly variable. Over short time periods of less than several days, the wave field and beach form may remain relatively constant, so that sediment drifts largely in only one

direction alongshore. Consequently, the transport rate approximates a gross value for a particular beach condition. Over longer periods of time, the beach state changes, and becomes more representative of the overall range of conditions that can occur. Sediments move alongshore in both directions and at varying rates, so the rate over long time periods more accurately approximates a net value. Estimates should therefore be expressed with explicit reference to the duration and conditions under which they were made.

Because all estimates of transport rates require the making of frequently imprecise assumptions they may be described as upper- or lower-limit approximations, depending on the presumed discrepancies from exactness. For example, the gross transport rate is an upper-limit approximation of the net rate (Galvin, 1972). Potential transport rates from wave energy inputs are another. Beach changes at a littoral barrier are generally taken as lower limit estimates, since the traps are seldom completely efficient. Attempts are often made, when studying a coastal sediment budget, to give both an upper and a lower limit estimate, thereby providing a range within which the actual rate supposedly must fall.

Distinctions may also be made when estimating longshore transport rates, between the ways by which sediments are transported. Komar (1976) separates sediment transport rates into suspended load and bedload components, according to whether the material is moved alongshore within the water column, or in close proximity

and intermittent contact with the bottom. Experiments have shown that these two rates can vary greatly, with the suspended sediment moving faster along the foreshore than the bedload (Zenkovich, 1967). However, bedload is thought to make up the bulk of the foreshore volume (Komar, 1978).

The final aspect of how transport rates are described concerns the units by which they are expressed. Many estimates that are directly applied to coastal management problems express the rate indirectly in terms of the rate of advance or retreat of the shore-normal beach profile, in units of distance or volume per time period. Carrying on from this, the standard measure of longshore drift is the volume rate of transport (Q). This is given as units of in situ sediment volume moving past a point over a period of time. The usual units are cubic metres per year.

Tracer studies measure the rate of longshore transport as the average velocity (distance/time) of individual particles parallel to the shore. This can be related to the volume rate of transport by the equation:

$$Q = A V_s \quad \dots 2.7$$

with units;

$$x.y.z.t^{-1} = x.z. \times y.t^{-1}$$

where V_s is the average sediment particle velocity
alongshore

A is the cross-sectional area of the active beach

t is a unit of time

and x , y and z are the three dimensions of the active
beach; width, length and depth.

The migration of identifiable morphologic features alongshore has also been measured in terms of their velocities (Dolan, 1971 and others). The volume rate of transport that may be associated with this phenomenon should be calculable using the relationship described above, but this does not appear to have been tried.

Komar (1976a) states two advantages in expressing sediment movements alongshore as an immersed-weight transport rate (I_ℓ). The first is that I_ℓ has units of work, and so can be directly and consistently related to the longshore component of wave power P_ℓ , which has the same units. The second advantage is that I_ℓ takes into consideration the density of the sediment grains and the pore spaces between them, so that comparisons can be made between beaches of different mineralogical and granulometric (grain shape) characteristics. The immersed weight rate is related to the volume rate by the equation:

$$I_\ell = (\rho_s - \rho) \ g a' \ Q \quad \dots \ 2.8$$

where ρ_s and ρ are respectively the sediment and water densities

and a' is the correction factor for the pore space of the beach sediment.

(Komar, 1976a)

2.5 SOURCES OF ERROR

Although the available range of methods for calculating longshore transport rates are suitably diverse, no single approach has yet been developed that can be considered as sufficiently accurate in every - or perhaps any - case. Approaches to the problem are complicated by the fact that longshore sediment transport is the result of an indeterminable combination of process elements acting within a broader, complex system. The potential for errors to arise in the methodology and analysis of longshore transport rates tends to be unavoidably high as a result.

Measurement inaccuracy is the first major source of error that is usually encountered. The dynamic nature of coastal environments means that changes over time are more noticeable than in most other geomorphic landscapes, but the measurement of the changes is made difficult by the high level of energy within open-coast beach systems. The intricate concurrence of solid, liquid and gaseous media in a beach also hinders measurements of the environment, and demands a unique system of instrumentation. A reduction in accuracy is the price that must be paid in order to overcome these problems.

The determination of wave parameters are especially affected by these problems. The seemingly random, and forever mobile patterns of the sea surface contribute significant levels of error to estimates of even the simplest of wave parameters. The wave height, and angle of wave approach - basic variables that are known to have a major effect on the longshore rate of transport - have

often been quoted as two of the most difficult to determine accurately (Walton, 1980; Schneider, 1981).

Errors in the estimation of longshore transport rates may also derive from the simplification of the complex reality. The ideal methodology would take into consideration every process factor that could possibly affect the longshore movement of beach materials. It has been deemed necessary, however, to reduce the complex coastal environment to a system dominated by just a few factors. Various assumptions are made concerning the causes and effects of longshore sediment transport. In doing so, the influence of some variables becomes ignored in the final estimate of the longshore drift rate, and a degree of error is established.

Factors that are considered to be insignificantly influential are often collectively incorporated into predictive rate estimates as a constant coefficient (for example, the k value in equation 2.6). However, they are each of some importance to the actual rate of transport, and so together they can produce significant residuals from the predicted rate. Some of these variables may on their own have a major influence on the transport rate.

In many cases, elements of the Process-Response system shown in Figure 1.3 are completely disregarded. For instance, the response-oriented littoral barrier method measures only the beach volume change resulting from all types of sediment movements, assuming (often incorrectly) that shore-normal transfers are negligible.

In comparison, the process-oriented Energy Flux Method measures only the capacity of the wave environment (the energy element) to move sediments alongshore, but, as Zenkovich (1967; 354) asserts, the flow may be undersaturated (and thus overestimated) if the supply of sediment is insufficient. Additionally, such methods seldom consider the morphologic influence of beach state, and especially antecedent morphology, on the processes and rate of longshore sediment transport. Komar (1976b) states that rhythmic topographies created by the redistribution of beach sediments have a strong feedback in controlling the nearshore currents, and must be included in models for a more complete understanding of sediment transport. However, he adds that it is first necessary to better understand the less complex case of longshore current and sand transport distributions on beaches where topographic effects are minimal.

The interpretation of transport rate estimates is the final major source of error in the approach to this problem.

It is important to recognise the type of estimate that is being dealt with. The units of all rate expressions are generally well-defined, but such aspects as their likely relationship to the true rate, and the scale of time and space at which they were calculated, are often more ambiguous. In order to reduce this source of error and to acknowledge all others, it is imperative that the nature and presumed degree of error of all rate estimates are positively defined.

When interpreting the results of a particular method for a specific situation, it is impossible to determine

the inherent level of inaccuracy, since this requires that the given result be compared to a standard 'true' value that in practical terms is itself indeterminable. Thus, the methods by which rates can be estimated cannot be calibrated in terms of their closeness of approach to a 'true' value, nor are they always strictly comparable one with another, because of differences in their measurement methods, derivations and assumptions.

Finally, the interpretation of rate estimates often involves their application to different situations or scales in time and space than those at which the estimates were made. The problem with such an operation, is that the multivariate nature of longshore sediment transport means that rates may vary greatly under only slightly altered process conditions, and so are constant in neither time nor space. Because of this, estimates of longshore transport rates made for one situation may not be very representative when applied to another. Consequently, Harvey and Bowman (1987) affirm that any extrapolation of transport rates to other spatial or temporal frameworks should be done with caution.

2.6 CONCLUDING REMARKS

The practical solution to the problem of determining the rate of longshore sediment transport on beaches has come a long way in the last forty years. The blossoming of coastal geomorphology after World War Two brought with it new perspectives for viewing the coastal environment. Many methods have subsequently been developed to complement the 'traditional' ones based on beach changes near coastal

structures. The present state-of-the-art sees the development of few truly new methods for estimating transport rates, but rather a reworking and modifying of the established methods, and application of these to practical situations. In some ways, longshore transport research appears to have come the full circle: as in the earlier part of this century, the established theories and methods are now being applied and assessed in situations where coastal processes present a practical problem. The only difference is that the methods available now are more numerous, more diverse, and more accurate than those previously utilised.

The estimation of longshore transport rates is nevertheless still a major problem in coastal studies today. Smith and Piggott (1987; 17) concede that;

"Because of the complexity of the interaction of many concurrent beach processes, littoral drift is one of the most difficult of beach behaviour parameters to assess. Many theoretical formulae exist, but their overall coefficients must be manipulated almost by a magnitude if their "answers" are to look at all reasonable."

The saving grace of the present situation appears to lie in the diversity of methods available.

Diversity within a methodology is an important attribute for two reasons. Firstly, it permits the use of an alternative method when the original one is found to be unsuitable for the case in question. At the present level of knowledge, it is unlikely that any given case of longshore sediment transport cannot be evaluated by at least one of the available methods. Secondly, diversity allows the reinforcement or reduction of rate estimates

obtained by a variety of methods, thus enabling a final estimate to be made with a greater degree of certainty or at least a specified range of uncertainty. A diverse methodology can therefore compensate for any lack of accuracy or universality that may be evident in the methods themselves. It has been made clear in this chapter that such compensations are highly desirable for the calculation of longshore transport rates.

CHAPTER 3

SAND AND GRAVEL BEACHES - A NEW SITUATION

3.1 INTRODUCTION

It was noted in Chapter One that the scientific literature dealing with the subject of longshore sediment transport is dominated by work on sand beaches. This work was reviewed in Chapter Two. Some work has also been done on coarse-grained pebble beaches (for example, by Jolliffe (1964) and Carr (1971) in England, Zenkovich (1967) in the Soviet Union, and van Hijum and Pilarczyk (1982) in the Netherlands). Beaches of mixed sediment composition, though, have been less thoroughly explored in coastal studies. It is this third type of beach - the mixed sand and gravel system - with which the present thesis is concerned. Such beaches possess an environment that is quite different to the more widely studied situations. Prior to examining the longshore transport regime on mixed sand and gravel beaches, it is therefore necessary to achieve some understanding of the process-response environment within which the phenomenon operates. With that objective, this chapter will introduce the study area, and describe aspects of the coastal environment that are important to the study of longshore sediment transport on mixed sand and gravel foreshores. A comparison will then be made of the foreshore environments of a mixed sand and gravel beach, and of the pure sand beach situation that

dominates the literature. This will provide a background for the later chapters, in which the processes, patterns and rates of longshore sediment transport on sand and gravel beaches will be examined.

3.2 THE SOUTH CANTERBURY COASTAL ENVIRONMENT

The South Canterbury coast, on the east coast of the South Island, New Zealand, was chosen as the study area for this thesis. A map of the study area, between the Waitaki and Opihi Rivers, is shown in Figure 3.1. This 80-kilometre section of coast is part of an extensive open-coast system along much of the east coast of New Zealand, where mixed sand and gravel beaches dominate the landscape. It is an ideal site for the study of longshore transport, not least because of the widely recognised dominance of the northerly drift of beach material on the sediment budget of the coast; the phenomenon has been noted for at least a century (Clarke, 1921). Longshore drift has created social and economic problems, with accumulation and erosion occurring at several locations along the coast. Numerous studies of the South Canterbury coast have been undertaken in attempts to resolve these problems (e.g. McIntyre, 1958; Hewson, 1977; Kirk, 1987), and an extensive literature and data base for the study area are becoming available (Todd, in prep.)

A large component of the research was undertaken on South Beach, Timaru. This 2-kilometre stretch of mixed sand and gravel beach lies in the northern part of the study area, and has been significantly altered as a result of port constructions at Timaru since 1878. Plate 3.1

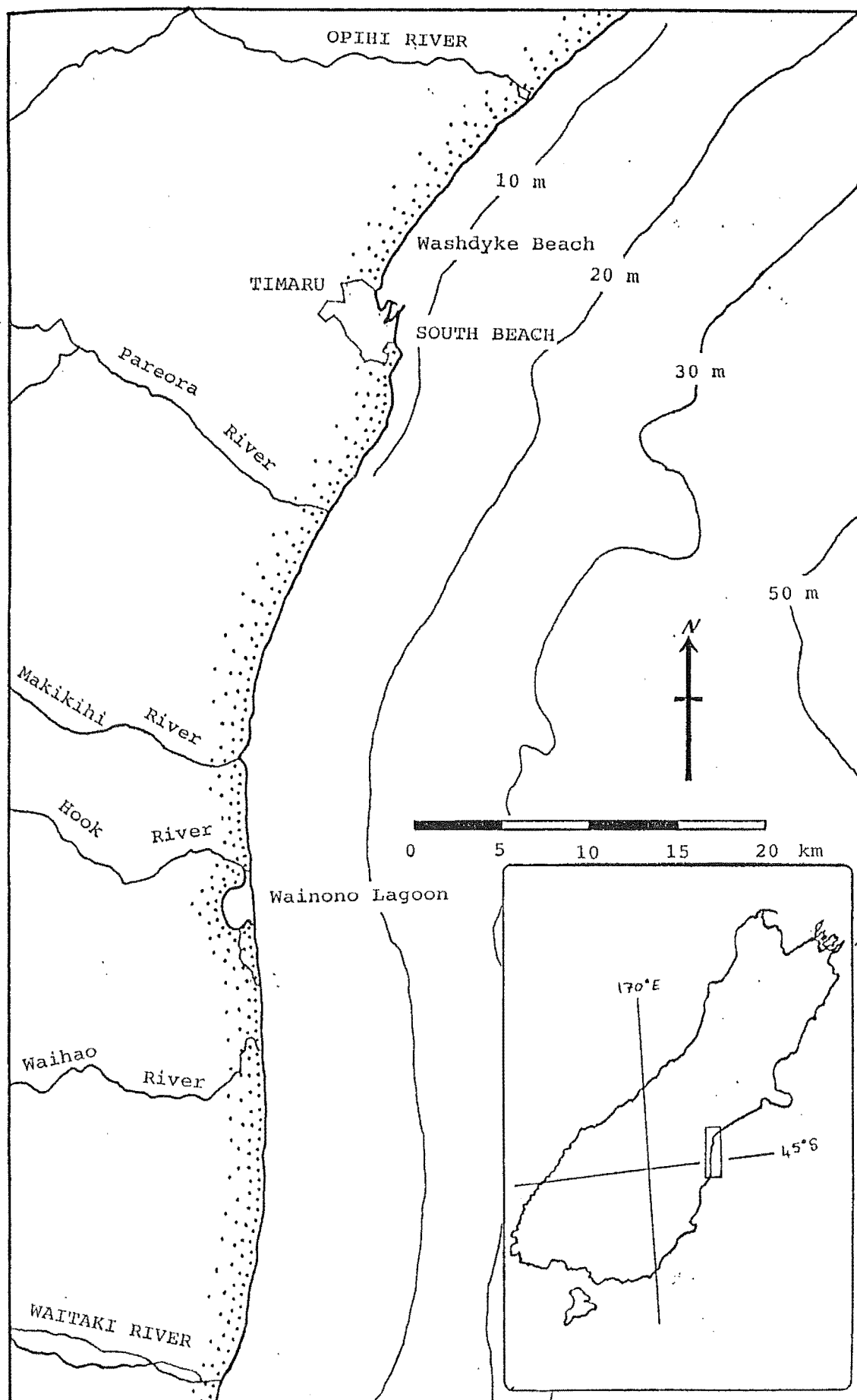


Figure 3.1 The study area between the Waitaki and Opihi Rivers.

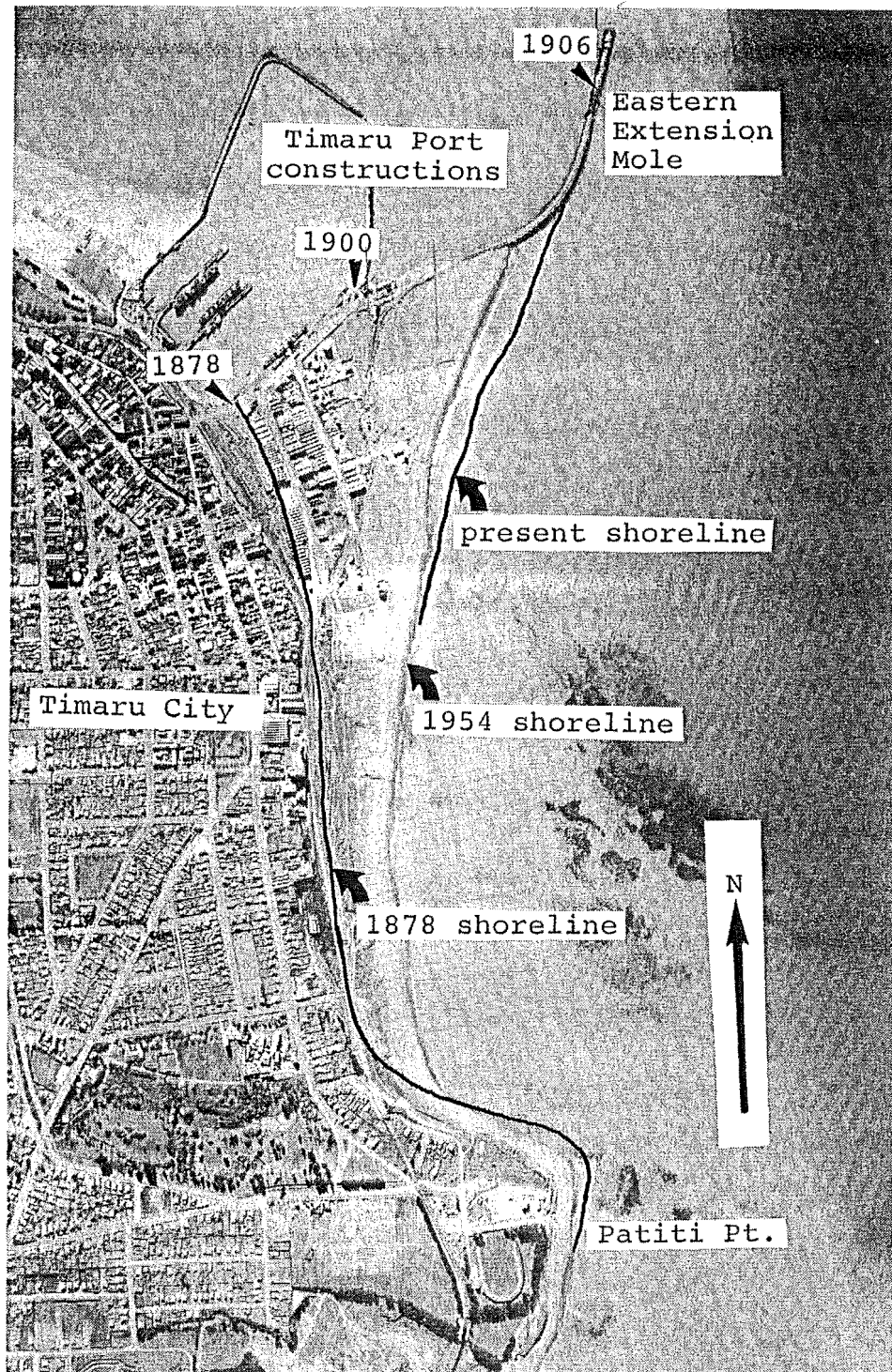


Plate 3.1 The main study site - South Beach, Timaru.
 (Air photo: Dept. Lands and Survey, 1954:
 SN802-2108/37)
 Altitude: 12000 ft.

shows that South Beach has prograded some 500 m along the Eastern Extension Mole, which was laid down to protect the harbour from the direct impact of storm waves from the southeast quarter. The accumulation of sand and shingle on South Beach has conveniently provided a large area adjacent to the port and the railway that is suitable for industrial development. The nature and magnitude of the shoreline changes at South Beach will be examined in Chapter 5.

3.2.1 Shore Geometry

The broad geometry of the study area is not highly complicated. From the Waitaki River, the shoreline has a roughly north-south orientation, but sweeps around in a broad arc further north, to lie along a northeast-southwest axis at the Opihi River. The smooth curve of the coastline is intersected by numerous rivers and lagoons, but is significantly broken only by the basalt reefs and port constructions near the city of Timaru. The beaches form the seaward margin of the extensive alluvial fan system of the Waitaki River and lesser streams, and are backed along much of the coast by cliffs and lowlands that are composed of coarse alluvial gravels and fine loess deposits. Off-shore, the bathymetry of the continental shelf roughly parallels the coast and the bottom gradient adjacent to Timaru is a gentle 1 in 500 to a depth of 200 m.

3.2.2 Wave Energy

The wave environment of the region classifies broadly on Davies' (1972) scheme as an 'east coast swell' type.

The length of the fetch from the southeast quarter is great enough to be described as unlimited, so the wave conditions approaching the coast are of a wide range in terms of power and direction. Waves are generated in the southern Pacific Ocean by a variety of meteorological wind systems, with the dominant (most powerful) waves originating from cyclonic weather systems to the south of the study area.

Refraction and shoaling alters the wave fields as they propagate shoreward. The depth and low gradient of the continental shelf means that the effect of seabed friction is low, so that the propagation of waves across it is not affected to an extreme degree.

The long period tidal wave ($T \approx 12$ hours) produces offshore currents that flow freely across the shelf, so the tidal range is relatively small, producing semidiurnal (spring) sea level variations of around two metres at the coast. Similarly, the wave field is transformed to some extent by shoaling processes, but much of the deepwater wave energy is retained well into the nearshore zone, and up to the foreshore. Frictional effects are nevertheless sufficient to redirect the dominant southerly waves by up to 40° or more before they reach the shore. Waves from the easterly quadrant are less affected by refraction, since their deepwater approach is closer to the optimal state of propagation; that is, perpendicular to the bed contours. Figure 3.2 shows that the prevailing (most frequent) wave direction at Timaru is from the southeast, with the waves from the east, although often less powerful, being almost as common.

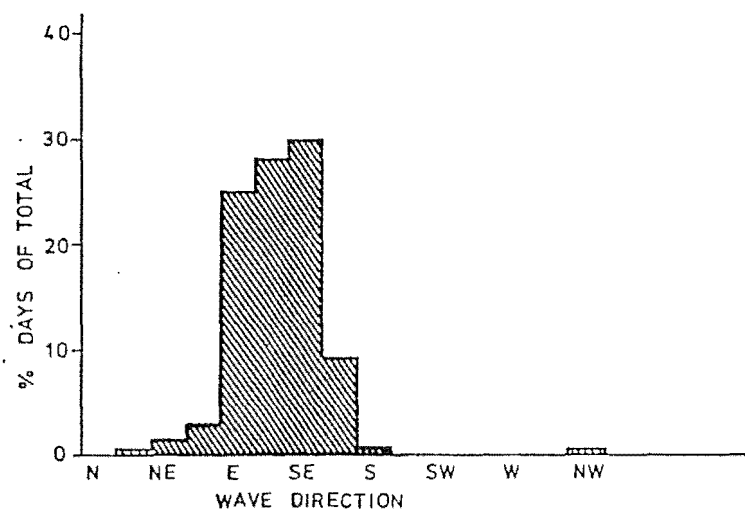


Figure 3.2 Wave direction at Timaru.
Source: Tierney (1977)

Sediments

The coastal sediments of South Canterbury have a very distinctive distribution. In the nearshore zone, seaward of the breakers, and below a depth of between approximately one (Tierney, 1977) and six (Kirk, 1980) metres below mean sea level, the seafloor is mantled by a very uniform layer of fine and very fine sand with occasional patches of gravel or silt (Kirk, 1977). In contrast, the foreshore zone is composed of much coarser sediments, typically dominated by coarse sand and gravel. This textural distinction brings to notice the distinctly different and quite separate transport systems of the nearshore and the foreshore zones. On the inner continental shelf, the nearshore transport system operates to move fine sediments by the oscillatory action of wave motion and by ocean and tidal currents, at a net rate northwards of approximately $650,000 \text{ m}^3 \cdot \text{yr}^{-1}$ (Kirk and Tierney, 1978). Sediment transport in the nearshore zone has a significant economic impact on the city of Timaru, since it causes the siltation of harbour channels that require regular dredging, and also the accretion of Caroline Bay, a backwater for nearshore sediments that now forms a popular swimming beach immediately north of the harbour. The nearshore transport system has been the subject of studies by Kirk (1977), Hastie (1983), Fahy (1986) and others, and will not be discussed in this thesis.

The focus of the present study is on the foreshore transport system of coarse material landward of the breaker zone. The present trends of widespread and rapid coastal erosion along most of the study area suggest that the budget of the foreshore sediments is of great significance

to the management of the coast. In addition to the long-shore transport, the sediment budget of this mixed sand and gravel beach system is characterised by several other sources and sinks. These were summarised in the Sediment Budget Model (Figure 1.4), and have been closely scrutinised over the past twenty years.

The sediments of the South Canterbury coast are predominantly derived from the greywacke rock of the South Island's Southern Alps. According to Kirk et al (1977) and Gibb and Adams (1982), the major source of supply of foreshore materials is the fluvial gravel deposits of the hinterland. Gibb and Adams (1982) estimated that the 37 km of high coastal cliffs north of Oamaru contribute 0.6 million tonnes ($334,000 \text{ m}^3$) of gravel to the beach system per year, whereas Hewson (1977) calculated a total volume rate of sea cliff supply (all grain sizes) of only $165,000 \text{ m}^3 \cdot \text{yr}^{-1}$. Hewson (1977; 69) provided evidence that the rate of supply by the cliffs can vary considerably, being dependent mainly on the saturation of the cliff top and the storm wave attack on the base.

Direct contributions of coarse sediment from the rivers are generally thought to be of lesser significance, providing only 15-20% of the total foreshore sediment budget (Kirk et al, 1977). The largest river source for the beach system is the Waitaki River, located at the southern limit of the study area. Estimates of the coarse sediment load entering the beach system from this river have been made by several authors, and three of these are summarised in Table 3.1. From these, it appears that only an 'order of magnitude' estimate is presently possible. In addition, the coastal supply rate by rivers is likely to

be highly variable, depending sensitively on the flow intensity and the mouth dynamics of the river (Young and Jowett, 1982). Other rivers draining into the study area contribute considerably less bedload sediment, with only the Opihi and Pareora Rivers exceeding even 10% of the Waitaki output (Gibb and Adams, 1982).

Table 3.1 Estimates of coarse sediment supply from the Waitaki River

Source	Supply estimate ($\times 10^3 \text{ m}^3 \cdot \text{yr}^{-1}$)	Notes
Kirk and Hewson (1979)	164	gravel load
Adams (1980)	99	bedload (incl. coarse sand)
Young and Jowett (1982)	31-42	gravel load

Only one other sediment source is likely to significantly contribute to the South Canterbury foreshore, and that is the nearshore continental shelf. Kirk (1967) considered this possibility, but concluded that the fine offshore sediments are seldom capable of remaining within the high-energy foreshore. In a more detailed study of nearshore sediments, Hastie (1983) found that coarse material could be transported landward onto the foreshore face, but the natural abundance of coarse particles on the nearshore bed surface appears to be low. Onshore transfers of sediment are still of an unknown magnitude, but appear likely to be relatively low.

Losses of sediment from the foreshore are thought to occur mainly via the offshore boundary. The coarse foreshore

materials are abraded by the impact of energy on the beach face, and as a result, large volumes of fine sediment (87% of the total budget, according to Gibb and Adams, 1982, but less than 50% according to Kirk and Hewson, 1979) are removed to the lower energy nearshore shelf. Losses to the backshore can and do occur by the overwashing effect of storm wave runup, particularly on lagoonal barrier beaches where the backshore slopes downward to the hinterland, preventing the return of overwashed material in the backwash. However, because of the present retrogradational (back-wasting) nature of the South Canterbury coastline, these losses can often be regarded as only semi-permanent.

All other gains and losses of sediments in a mixed sand and gravel foreshore can be attributed to longshore transport. Coastal winds are of little direct significance to sediment movements (Kirk, 1980), and the high mobility and infertility of the beach materials are not conducive to the production of biogenous materials.

3.3 SEDIMENT TRANSPORT BY HYDRAULIC ACTION ON SAND AND GRAVEL SURFACES

Within the foreshore itself, the interplay of the 'external' process elements described above, causes the creation of 'internal' elements that constitute the distinctive process-response system of a mixed sand and gravel beach. The subsequent interaction of the internal process elements induces beach responses through the occurrence of sediment transport. On beaches, sediment transport is mainly caused by the action of hydraulic energy

on the cohesionless sediment matrix. Several fundamental aspects of the interactions between moving water and movable sediments are relevant to the mechanisms of sediment transport.

Pethick (1984) demonstrates how the force applied to a sediment bed depends on the velocity of the water flow across it. This 'shear velocity' is affected at any point on a sand and gravel foreshore by such factors as the energy of the incident wave, gravitational forces, and the dissipation of wave energy by various means (friction, noise, turbulence, etc.). The threshold shear velocity required for the entrainment (initiation of motion) of a sediment particle depends on the movability of the particle, which is mainly a function of granulometric parameters (size, density, shape), and the degree of packing of the bed. These critical velocities have been determined and are shown against grain diameters in Figure 3.3, along with the critical velocities for the deposition of particles in motion.

In general, lighter (finer, less dense) particles are more likely to become entrained than heavier (coarser, denser) particles, and less likely to be deposited once in motion. Also, because of the surface area that they expose to hydraulic shear forces, more spherical particles are more susceptible to both entrainment and deposition than less spherical (e.g. discoidal) particles. The close-packing of particles within a sediment bed, which mostly depends on the degree of sorting of the sediment into a small size range, promotes the stability and non-movement of individual particles, by reducing the exposed surface

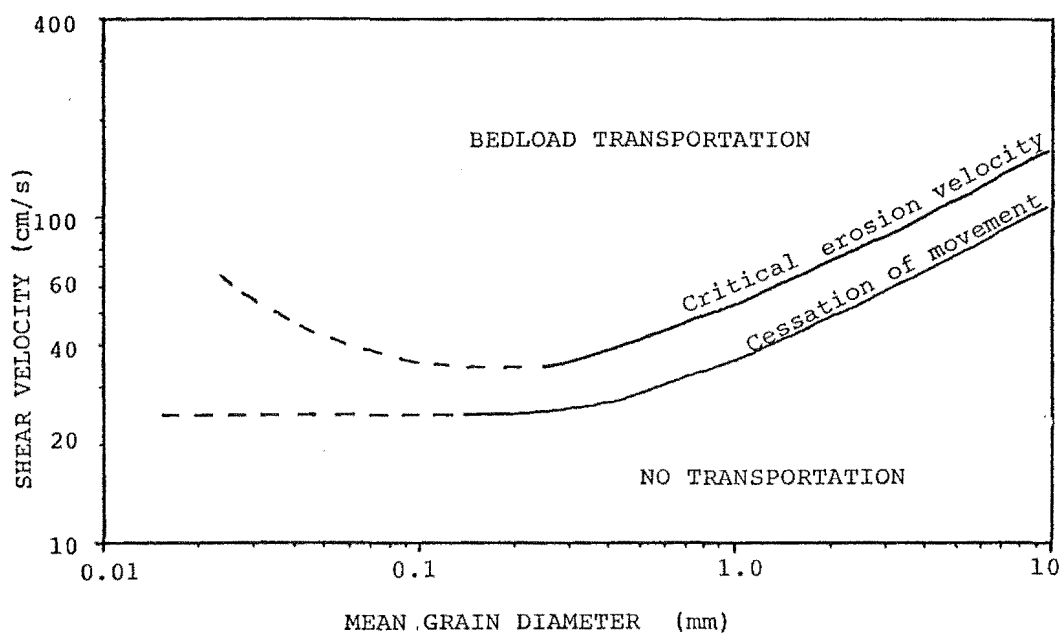


Figure 3.3 Critical shear velocities for the entrainment and deposition of particles by water.
(Source: Sternberg, 1971)

area and elevating the fulcrum around which the particle pivots (Pethick, 1984).

Because the sedimentary prism of a beach is a depositional landform, it is the deposition and non-movement (rather than the entrainment) of particles that is directly relevant to the beach morphology and sediment distribution. Particles are deposited only where shear velocities fall below the motion-deposition threshold. If deposited particles are subsequently not able to be entrained they will remain in the same location along with others of similar hydraulic behaviour. Therefore, areas dominated by low levels of energy are generally characterised by non-readily deposited particles (e.g. fine and/or discoid grains), whereas high energy areas can only maintain deposits of the more coarse and spherical particles.

The depth beneath the bed surface to which particles are moved by hydraulic forces (the 'depth of disturbance') is often important to the determination of sediment transport rates, but has been found difficult to determine. Most attempts have involved the insertion and recovery of a 'plug' of tracer material (e.g. dyed sediment grains); the depth to which the plug is replaced by native beach material being the depth of disturbance caused by hydraulic action. Williams (1971) showed that this depth is mostly reliant on the hydraulic energy level, and disagreed with the results of King (1951), who found a relationship (inverse) with the grain size of the material. If a relationship with grain size does exist, it is likely to be complex, since the depth of disturbance would logically increase with the transportability of the particles (favouring smaller grain sizes) and

with the penetrability of the water into the sediment matrix (favouring more permeable coarse-grained surfaces).

In summary, the transport of beach materials is dependent on the characteristics of the hydraulic energy and of the materials themselves. In accordance with the Process-Response framework, geometric characteristics are also a factor, but these are usually conditioned by the first two. On a sand and gravel foreshore, all three factors are highly variable. Given the wide range of material characteristics that is notably unique to mixed sand and gravel beaches, the physical processes of sediment transport on such beaches become so much more complex.

3.4 MIXED SAND AND GRAVEL FORESHORES

The beach surface of a mixed sand and gravel foreshore was shown in Figure 1.5b to be typified by a narrow, steep profile, approximately 100-200 m wide and rising 4-6 m above mean sea level (Kirk, 1980). The seaward limit of the foreshore at the breaker zone is clearly delineated by abrupt changes in all three types of process elements. The geometry of the profile at this boundary changes sharply with a landward increase in gradient, while the material composition becomes much coarser and the rate of wave energy dissipation grows. These changes are closely linked by strong feedback relationships, with each element promoting the maintenance of the other two. The landward foreshore limit is marked by a nearly horizontal storm surface, or by the base of either a cliff or a washover slope, all of which represent quite clearly, the extent of storm swash.

Between the two profile limits, the foreshore exhibits a distinctive morphology comprising five major slope facets, as illustrated in Figure 3.4. It has been very well documented in the literature that a change in beach slope over time or space indicates an equivalent change in the process environment that controls it (e.g. Wright et al, 1979; McLean and Kirk, 1969), and that a constant slope implies a relatively constant process environment. That the internal process elements of a foreshore system do not act uniformly throughout the foreshore is proven by the obvious non-uniformity of the beach profile through time and space. The foreshore is not a homogeneous 'process unit', but can be subdivided into separate, though related zones on the basis of spatial variations of the process and response elements within it. For convenience then, the foreshore can be divided into five subzones, with different surface gradients, that may prove to be characterised also by distinctive process interactions with coinciding spatial boundaries.

Previous investigations of beach foreshores have made this subzonation of secondary importance in the comprehension of foreshore dynamics, by making first-order reductions of the environment into the energetic, sedimentary and geometric components, in line with the approach suggested by Krumbein (1963) in the Process-Response Model (in Figure 1.3). Only after that, is the spatial subzonation across the foreshore profile usually considered, if at all. This approach has been used effectively to describe foreshore systems in general terms (e.g. Hewson, 1977; Kirk, 1980; US Army, 1984). However, it does not adequately emphasise the great variability of the process interactions

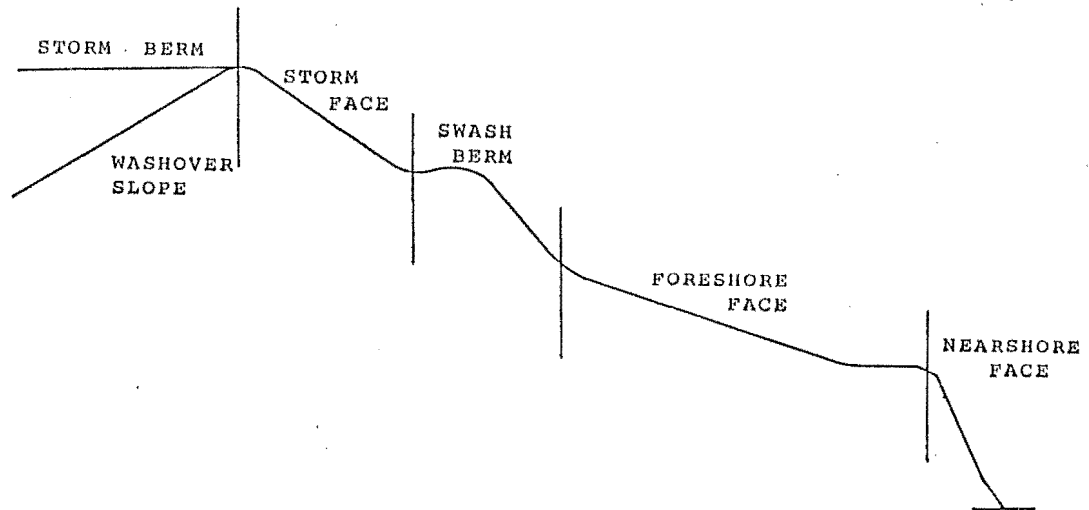


Figure 3.4 Slope facets of a mixed sand and gravel foreshore.

at different locations within the foreshore. More importantly perhaps, it neglects, to some extent at least, the intricately related and contemporaneous influences of innumerable process factors at any location on the foreshore.

A more appropriate description of the foreshore for process studies such as this and others would make first-order considerations of spatially separated 'process zones', with second order isolations within each zone, of the Krumbein process and response elements. It is to be maintained that within each zone, all of the elements interact with each other, striving to attain an optimal condition at which they are in a stable equilibrium and further net exchanges of beach material become unnecessary. This approach has often been adopted when distinguishing between the separate, though related, nearshore and foreshore sediment transport zones of the South Canterbury coast (e.g. Kirk, 1977; Gibb and Adams, 1982; Hastie, 1983), but has not been widely extended one step further for use within the foreshore zone. A possible reason for this is that, unlike the nearshore-foreshore interface, boundaries within the foreshore are more difficult to define, and are seen to be more mobile over time. Although this may be true, it will be shown in this chapter and the one following, that this approach to process interactions on foreshores is both valid and useful.

The nearshore face

This seawardmost subzone is the one least well understood, because of the difficult, turbulent and high energy conditions that characterise it, and that hinder

on-site measurements. Several features, however, are widely noted. Kirk (1980; 194) states that "the nearshore slope is composed of coarse gravels and cobbles standing at or near their angles of repose". The particles in this zone are mostly rod- or sphere-shaped (after a classification by Zingg, 1935, in Krumbein and Pettijohn, 1938; 228), having low critical velocities of entrainment and deposition. In addition to this, their coarseness gives them a relatively low mobility.

It is also asserted by Kirk (1980) that "the presence of the nearshore face...exerts controlling influences on the location and pattern of wave breaking". The vertical height and position of the nearshore face in relation to the sea surface, and the control exerted on wave breaking by the water depth, mean that all incident waves must break onto the upper section of this slope. Consequently, the waves break in a zone that is no more than a few yards wide and that is not significantly translated across the profile with the rise and fall of the tide. The steep face dissipates and reflects a large proportion of the high levels of incident wave energy, and so plays an important role in the protection of the hinterland from wave attack.

Much of the energy that is dissipated in wave breaking contributes to the movement of sediments. The efficiency of a wave in transporting beach material on the nearshore face depends largely on the way in which it breaks and the rate at which it dissipates energy. This is determined by the initial wave shape (an external parameter) and the beach slope (an internal parameter of the nearshore face) (U.S. Army, 1984). Since the gradient of a slope facet is positively correlated with the wave

energy and the grain size and sorting of the constituent materials, it is clear that the transport of sediments in this zone is highly complex. It has been proven in a tracer experiment by Hastie (1983) that particles are able to move up the nearshore face and onto the foreshore, but little is known of the hydraulic circulation and sediment transport mechanisms of the breaker zone, and the responses to process inputs of the face itself.

The foreshore face

Immediately landward of the breaker zone is the foreshore face, a slightly concave surface inclined at about $5-12^{\circ}$ that is composed of well sorted sediments (i.e. with a narrow size range), usually of the coarse sand to gravel sizes. The low mass of these particles means they are readily movable by the transfer of energy from the flow of water across the face. The unspent wave energy from the breaker zone exerts an influence on the foreshore face in the form of a physical translation of water mass across the slope (swash). The face is alternately dominated over cycles of about 10 seconds by the upslope flow following the breaking of a wave (uprush), followed by the seaward return of the water downslope under the influence of gravity (backwash).

The width of the foreshore face is determined by the length of the swash. The swash length (measured horizontally normal to the shore from where a wave breaks to the landward limit of the swash) has been found, in the course of field research for this thesis, to be positively correlated to the height of the associated incident breaker, as shown by

the graph in Figure 3.5a. This result compares well with that of Kirk (1975) for mixed sand and gravel beaches near Kaikoura, New Zealand, also shown on the graph. The scatter of the data points is partly due to the values being averages over several minutes, so that single swashes were not compared directly to their causative breakers, but instead to those in the same wave group. The slopes and coefficients of the regression lines in Figure 3.5b show that the breaker height has less influence on the horizontal swash length when the breaker exhibits pronounced vertical dissipation of energy by 'plunging' onto the nearshore face. The energy of 'spilling' breakers, which retain a comparatively greater component of horizontal motion, is represented more accurately by the length of their uprush.

Only a portion of the initial wave velocity is translated into uprush flow parallel to the bed. This was found by Kirk (1975) to decrease from 60% for low energy waves, down to 20% for waves with two orders of magnitude greater energy. His measurements also showed that most of the uprush velocity is maintained right across the foreshore face, but some of the mass is lost from the surface by percolation of the water vertically through the sediment matrix. The backwash phase is characterised by lower velocities and a longer duration compared with the uprush, but is also quash-constant across the foreshore. As a result, the slope and surface sediment features are reasonably constant across the face.

Materials at and near the surface are moved across the foreshore face in the direction of the swash. The moderately high energy levels, and the high sediment mobility

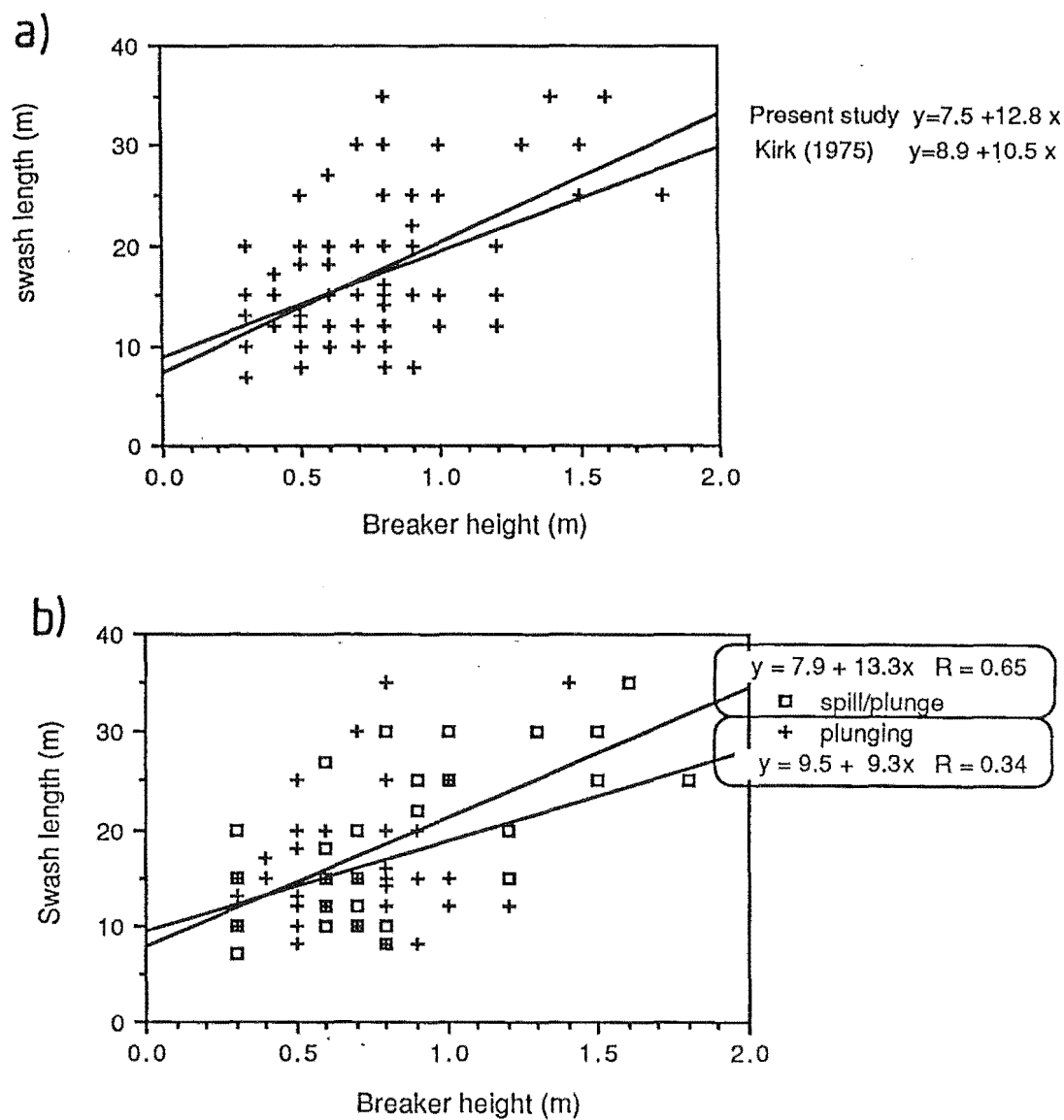


Figure 3.5 a) Relationships between breaker height (H_b) and swash length (l_s) at South Beach, Timaru. $N=78$ $r = 0.56$

b) The influence of breaker type on the relationship.

make sediment transport of great importance in this subzone. For this reason, and because of the considerable distance over which the flow of swash occurs, the foreshore face, or swash zone, has been described by Kirk (1980; 1993) as "the 'engine room' of mixed sand and gravel beaches".

The Swash Berm

At the top of the foreshore face, the beach surface begins to level out, and a convex slope facet often exists at the upper limit of the swash. This morphologic feature is commonly termed the swash berm; its position on the beach profile (i.e. its distance from the breaking waves and height above sea level) is variable, and directly dependent on the existing and recently antecedent length and runup height of the foreshore swash. The exact location of the boundary between the foreshore face and the swash berm is difficult to determine from the profile geometry alone. However, changes in the sedimentary and energetic elements can be identified in the vicinity of the change in slope, and these may help to identify the boundary more adequately.

The surface materials of the swash berm tend to be coarse and disc-shaped. Such particles settle only under low flow velocities, so their presence on a surface suggests the occurrence of low energy conditions. This suggestion has been upheld by results from two studies of note. Pyshkin (1954, in Zenkovich, 1967) found that the wave uprush, at 75-80% of its overall distance, ceases moving in a continuous mass, and divides laterally into separate tongues. Measurements made by Kirk (1975) are graphed in Figure 3.6, and show that this same location is marked both by sharp reductions in the high uprush velocities maintained

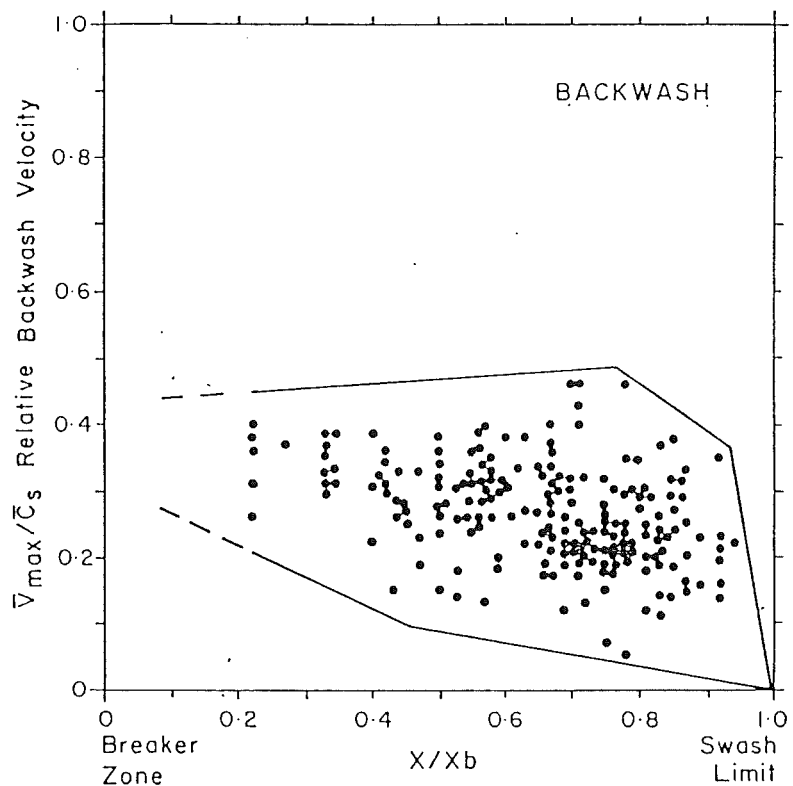
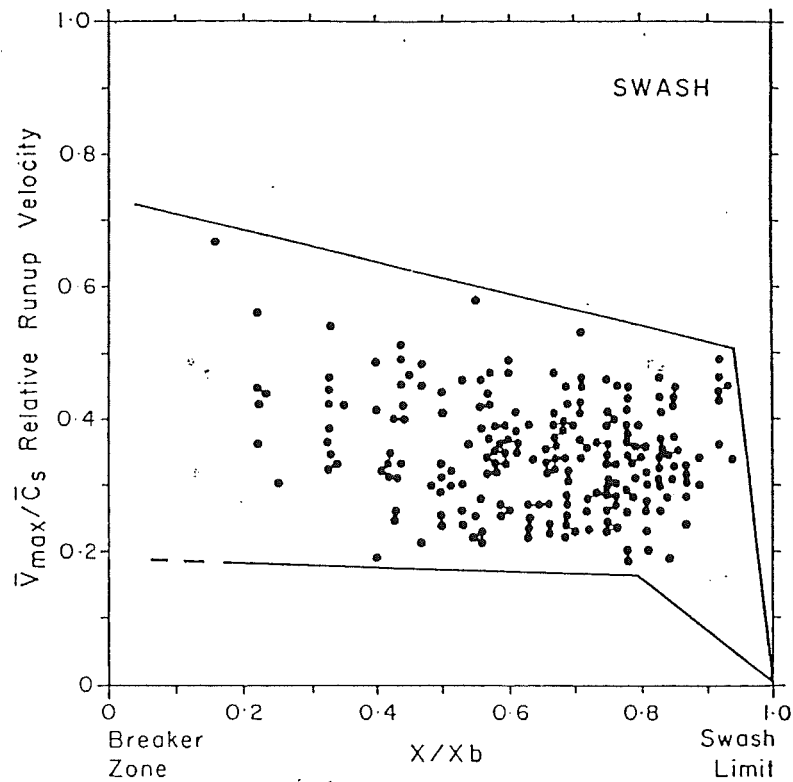


Figure 3.6 Relative runup and relative backwash distributions across the foreshore. The velocities are expressed as ratios of the calculated breaker speed. Note the sharp changes in the swash velocity where $X/X_b \approx 80\%$.
Source: Kirk (1975)

across the foreshore face, and by a fall in the acceleration of the returning backwash. This shows that low energy flows are indeed a feature of the upper swash zone at the berm. That the flow velocity across this zone is not constant, but falls to zero at the landward margin, is reflected in the non-constant gradient of the convex slope facet.

Topographic features known as beach cusps are largely confined to the swash berm. They exhibit a rhythmic pattern alongshore of high and low points on the berm crest combined with deposits of coarse and fine material respectively, with spacings of around 50 metres. Their modes of formation on sand and gravel beaches have not been studied, but they are likely to be related causally to the velocity changes and lateral divisions of the swash that occur in this subzone. Strong positive feedback relationships are likely to occur to maintain and strengthen the cusped forms.

The Storm Face

By definition, the swash berm makes the landward limit of the recent swash. If the swash length increases, as during a storm, the swash berm will be translocated upslope, or destroyed, and the beach surface further to landward will become an active part of the swash zone. Unlike the foreshore face, this surface is acted upon only intermittently, and only by the swash of the larger storm waves. Under the normal conditions of low swell waves, the surface exists as a virtually inert 'storm face', with a gradient somewhat lower than that of its associated foreshore. It possesses many similarities to the foreshore

face, since both are formed by the action of swash. The major difference though, is the much larger scale of operation, and the level of energy that is spent in shaping the storm face. Higher input levels of wave energy tend to create lower slopes, supply a wider range of grain sizes, and inhibit the deposition of smaller grain sizes. Consequently, a composition of poorly sorted coarse materials is a feature of the storm face. Significant amounts of finer gravels and sand may occur beneath the surface due to entrapment and percolation within the coarser matrix. The surface is usually interrupted by wrack lines marking the swash limits of moderate or receding storms.

More complex differences may arise due to the different interactions of the process elements. Such relationships are likely to be very different during storm and swell conditions. For instance, the swash period (the duration of the uprush phase) is an internal parameter that tends to increase with the swash length. It has been suggested by Kemp (1960) to have an interactive relationship with the incident wave period (an external parameter) that is very important to foreshore dynamics. Also, a higher degree of swash percolation is probable on the storm face because of the larger grain sizes and relatively lower water table, so that backwash processes may play a very different role in beach dynamics. The dynamics of this subzone are very hard to measure or evaluate as they occur, due to the difficult conditions that they inevitably entail. Nevertheless, it is quite reasonable to suggest that the contrasts between the foreshore face and the storm face are not solely of magnitude, but are also of process pattern.

The Storm Berm

The landwardmost slope facet of a mixed sand and gravel foreshore is often a near-horizontal surface marking the maximum runup height of the biggest storms. In much the same manner as the storm face discussed above, the storm berm is analogous to its lower-energy downslope counterpart, the swash berm. Again, the material is coarser and poorly sorted, the energy inputs are intermittently moderate, and the process interactions are likely to complicate the real situation.

The Washover Slope

In cases where the foreshore is not backed by a supporting natural or artificial vertical structure (such as a cliff), a more stable landwardmost slope facet is a reverse slope that extends down from an upper beach crest to a base level. This landform is most common on barrier beaches backed by rivers or lagoons, and occurs at numerous points along the South Canterbury coast. A major feature of these slopes is that they absolutely prevent the backwash of encroaching swash, which can cause flooding of the hinterland if backshore drainage and percolation are insufficient. Similarly, seaward sediment movement from this slope are impossible, so sediment transported by overwash onto the slope can be regarded as losses, though often only temporary, to the active beach.

Subzone Linkages

Five subzones, each characterised by distinct processes and responses, have been identified within the

foreshore zone of a mixed sand and gravel beach. The features of each subzone are summarised in Table 3.2. Because the differences are not solely morphological, but extend to the beach dynamics of each section, it may be useful to view these 'subzones' more as 'subsystems', possessing discrete process-response and sediment budget regimes that interact with those of adjacent subsystems. These interactions are of great importance to the overall development of the foreshore, just as nearshore-foreshore-hinterland interactions are important to the development of the South Canterbury coast.

The five subsystems of the foreshore are determined and linked by the inputs of external process elements from outside the foreshore zone. For a given external input or set of inputs, a certain type and magnitude of response can be expected in each of the subsystems. Similarly, changes in each of the subsystems are initiated and linked by the changing inputs of the external elements. Energy inputs are especially dominant initiators of subzone changes, since they are themselves highly changeable.

The primary linkage between the subsystems is the sequential transmission of hydraulic energy between adjacent zones. In general, incident wave energy enters the foreshore through the nearshore face (breaker) zone, a decreasing proportion of it propagating landward through some or all of the other subzones in sequence, and returning offshore as backwash through the subzones in reverse order. The amount of hydraulic energy that enters a subzone depends entirely on the initial level of energy entering the foreshore, and the proportion of it that is converted (dissipated

Table 3.2 Process-response subsystems of a
mixed sand and gravel foreshore.

Subzone	Nearshore Face	Foreshore Face	Swash Berm	Storm Face	Storm Berm	Washover Slope
GEOMETRY	steep	moderately steep (5-12°), concave, changeable	convex, variable size, shape and position	less steep (5-7°)	near- horizontal	reverse slope
MATERIALS	coarse gravels high settling velocity low mobility	gravels and coarse sand, high mobility, well sorted	coarse gravels high entrain- ment velocity low settling velocity, low mobility	coarse gravels moderately sorted	coarse gravels poorly sorted	
ENERGY FLUX	high, very turbulent, mostly shore- normal dissipation and reflection (breaker zone)	high, turbulent, increasingly shore-parallel, highly bidirectional (swash zone)	sharp drop in swash velocity, low potential, mostly shore- parallel, some vertical (upper swash)	intermitt- ently high, moderate obliqueness, some vertical (storm swash)	intermittently moderate, mostly shore-normal and vertical (upper storm swash or overwash)	

or reflected) by preceding subzones. Under low energy conditions, the incident energy is rapidly converted, and little or no energy is transmitted into the upper storm zone. Higher levels of incident wave energy will cause a greater rate of energy dissipation by waves breaking on the nearshore face, and a higher amount but proportionally lower degree of energy reflection. It will also increase the energy transmitted to the other zones, thus lengthening the swash on the foreshore face, elevating the berm, and activating part or all of the storm surfaces. The progressively lower levels of hydraulic energy that are transmitted between subzones by an advancing and receding swash lead to the development of the distinctively different process interactions and responses that become characteristic features of each subzone. Because of the close interactions between the energy, materials and geometry of a beach system, the subzone boundaries tend to be marked by coinciding changes in all three elements.

Sediment Transfers

A linkage that follows on from the transmission of energy is an equivalent transfer of beach materials, since sediment transport is a function of energy flux (as already demonstrated by the Energy Flux Method in Chapter Two). Particles are moved in the direction of, and at a rate proportional to, the hydraulic energy flux. Thus, providing that the flow is sufficient to initiate and maintain the movement of particles, the uprush of a wave on a beach causes onshore movements and the backwash causes offshore movement, with longshore components of movement usually occurring in both cases.

Cornaglia (1889) proposed that the optimal location of a particle across a beach is where its net shore-normal movement is zero (i.e. where the uprush and backwash displacements are equal). He named the location the 'neutral line' (on account of its continuation alongshore), and demonstrated its dependence on the energy flux strength, the slope of the face, and the weight and volume of the particle. Because of the marked differences between fore-shore subzones with respect to the first two of these factors, the neutral line of any given particle shape is unlikely to readily move between subzones. Each subzone thereby acts as the 'neutral line' of one or more sediment shape classes. Figure 3.7 shows that a particle above or below its neutral subzone will, because of its shape, be acted on unequally by the uprush and backwash until it is reintroduced into its optimal position on the profile. It is therefore likely that all beach particles remain predominantly within a subzone, excursions into adjacent zones being mostly occasional and temporary. It also follows that the subzone boundaries as defined by hydrodynamic (energetic) and sedimentologic processes should coincide.

A disequilibrium exists when the subzone boundaries do not coincide. This can be caused by rapid changes in energy inputs effecting a translation of the hydrodynamic subzone boundaries. The consequences of this are demonstrated in Figure 3.8, using the swash berm boundaries as an example. In (a), constant energy inputs maintain the subzone in an equilibrium position, with all process elements coinciding. Movements of material are mostly confined within subzones, and net movements are minimal.

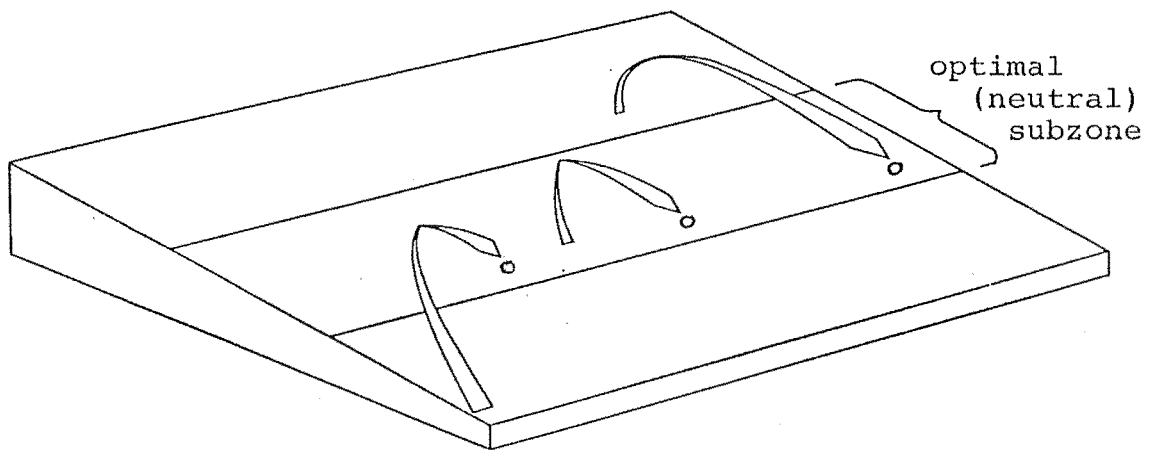


Figure 3.7 The reintroduction of a particle to its neutral subzone on the foreshore. Velocity of flow indicated by width of arrow.

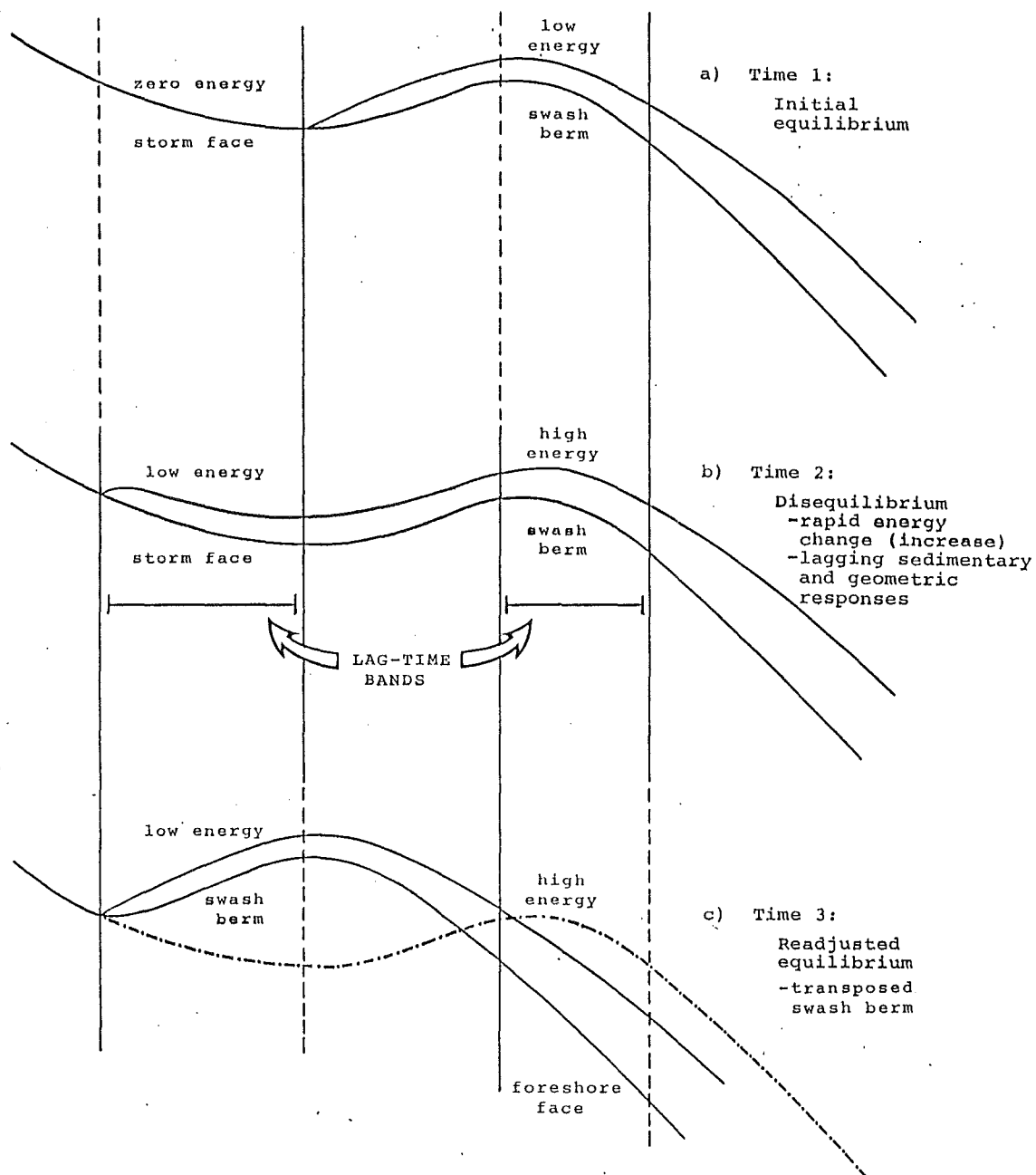


Figure 3.8 Disequilibria caused by an increase in wave energy (i.e. swash length) at the swash berm. Vertical lines mark subzone boundaries.

When the incident level of energy rises, as in (b), the hydrodynamic features that define these boundaries (e.g. a change in flow velocity) move landward, and the sedimentary and geometric boundaries are both put into disequilibrium. To regain equilibrium, sediments are moved until, after a certain lag-time, the sediments and geometry readjust to coincide with the new energetic boundary, as in (c). Until the readjustment is completed, the new and old boundaries enclose what can be thought of as a 'lag-time band', or zone of disequilibrium, that shares combined features of both subzones. Because changes in energy input vary even at the scale of a single wave period (i.e. faster than the lag time), adjustments are never fully completed, and the subzone boundaries are never in full equilibrium. Consequently, the transitional band always exists and the boundaries cannot be strictly identified.

Sedimentary and geometric elements may sometimes be prevented from adjusting to coincide completely with a new energetic subzone. Particles that are in disequilibrium with the energy are not moved if they become no longer a part of the active layer of the beach face. This can occur if the lag-time band experiences a marked drop in energy, as at the swash berm during the recession of a tide or storm. Figure 3.9 shows that the lower level of energy created by the seaward translocation of the energetic boundaries may not be powerful enough to relocate the materials within the bands to their newly defined subzones, so particles become stranded in isolation from their equilibrium subzone. The result of this can be seen on the

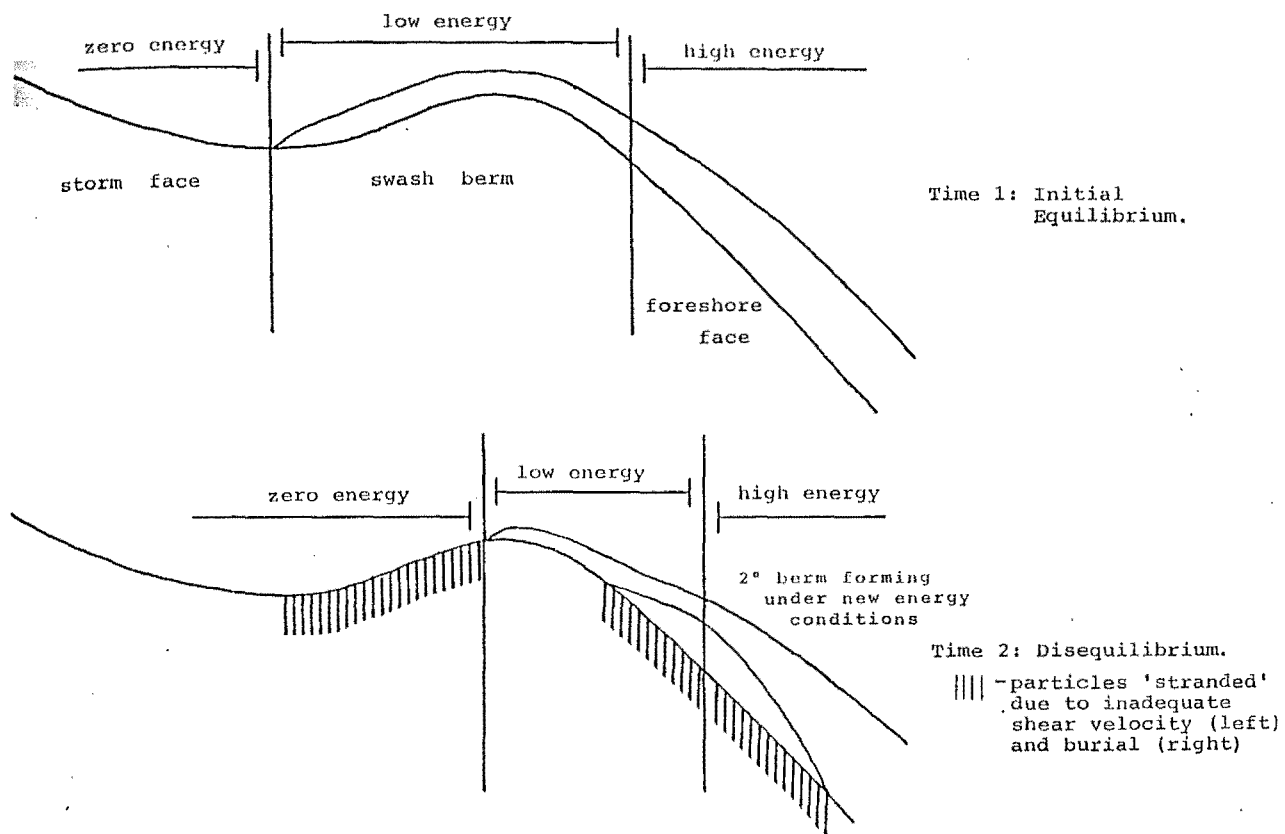


Figure 3.9 Stranding of particles by a drop in wave energy (receding tide or storm) at the swash berm.

storm face, where a receding upper storm swash often leaves stranded a mass of particles similar to those normally found on the lower foreshore. Particles may also be removed from the active layer by burial beneath other mobile sediments. Both of these mechanisms can result in the semi-permanent deposition of material high up or deep within the foreshore profile.

It follows from this discussion that the greatest transfers of sediment between subzones occur when the neutral lines (subzones) are being transposed by large changes (especially increases) in the hydraulic energy flux. These cause large movements of the energetic boundaries, which create wide lag-time bands. A greater volume of material enters disequilibrium with the energy level, and may be forced to move a considerable amount to regain equilibrium. A view similar to this is shared by Wright et al, (1985), who defined a formula for the 'disequilibrium stress' on a sand beach under changing wave conditions, to give an indication of the expected rate in beach state over time. The proposition is also demonstrated by the results of Siemelink (1984) on a mixed sand and gravel beach, which note changes in the profile shape (i.e. in the transverse distribution of sediment) that correlate to rises and falls in the wave power.

3.5 A COMPARISON WITH SAND BEACHES

The sandy beach type, on which most of the present understanding of longshore sediment transport has been developed, is quite unlike the mixed sand and gravel type described above. By definition, the grain size composition

is an essential difference of the two types. The occurrence of 'material factors' on both sides of the Process-Response framework (Figure 1.3), and their great significance to the kinematics of beach systems, suggest that other important differences derive directly from this contrasting feature.

The beach surface of an open-coast sandy foreshore was shown in Figure 1.5a to be typified by a broad, low-gradient profile, approximately 100-300 m wide and rising 1-3 m above mean sea level. The geometric subzonation of the profile is much less obvious than that of mixed sand and gravel beaches, mostly because the small size range of the sediments permits only a small range of slope gradients to be produced ($0-2^{\circ}$). Consequently, the energetic subzonation is also indistinct. Breaker, surf and swash zones are often noted, but the boundaries between them are not sharp, nor are they easily definable. For this reason, sand beach systems are discussed in the literature usually in terms of their overall geometric, energetic and sedimentologic components.

The profile of a sand beach is much less steep than that of a mixed sand and gravel foreshore, and the landward and seaward boundaries are not the same. The seaward limit of the foreshore is marked by a convex break in slope, at which the larger storm waves break. Sand dunes, formed by the deposition of wind blown sand from the exposed beach face, approximately mark the landward limit. Between these two boundaries lies a topography that is often complex, consisting of subaqueous bars (longitudinal mounds of sand) and troughs, and a low subaerial berm and swash zone imposed on the lower section of a storm face. The morphodynamic model developed by Short (1978) and others, shows

that the slope facets and distribution of sediments across the profile of a sand beach are numerous, and are readily adjusted by changes in the incident wave energy and the inshore circulation of water. In addition, longshore rhythmicities such as subaerial cusps and subaqueous crescentic bars frequently extend the topographic complexity into the third dimension. The geometry of a sandy foreshore thus appears to be considerably more complicated than a sand and gravel beach morphology.

The patterns of wave energy dissipation, reflection and circulation within the foreshore of a high-energy sand beach were demonstrated by Wright, ~~L.D.~~ et al, (1978) to be greatly influenced by the three-dimensional geometry of the beach surface. When the foreshore is wide and flat (a condition produced by high levels of wave energy), the waves first break a long distance offshore. Propagating across the surfzone, the waves reform and may break again on an inner bar or the foreshore (swash) face. Unlike the primarily vertical and temporal segregations of onshore and offshore water flow on mixed sand and gravel beaches, circulation flows on a sand beach foreshore are usually in all directions at the same time, in the form of a rip cell around a vertical axis. The surfzone is the dominant region of sediment transport under these conditions. When the foreshore is narrow and steep (a condition caused by prolonged periods of low swell, and rather rare on open-coast sand beaches) the waves break close inshore, much of the energy is reflected, and swash zone processes become more important in transporting materials. This condition is a little more closely comparable to that of mixed sand

and gravel beaches, but it is not subjected to significant rates of longshore transport, because of the low energy levels.

The feedback mechanisms of antecedent beach morphologies on foreshore circulation patterns ('topographic forcing') are made significant by the high geometric variability of sand beaches. Consequently, the spatial and temporal complexity of sand beach morphology can similarly complicate the energy flows. Compared to narrow breaker zone and parabolic swash flows that dominate mixed sand and gravel beaches, sand beach circulation appears to be very much more difficult to model or to understand.

The basic granulometric difference of the sediments of mixed and sand beaches has implications for sediment transport that were discussed in Section 3.3. Zenkovich (1967) suggested that this feature alone makes mixed beaches the more complicated, because of the different ways in which the separate sediment components are displaced. It is often supposed that the wide size range can lead to the simultaneous occurrence of bedload, saltation and suspension transport. However, the almost complete clearance of water from the foreshore by backwash, suggests that suspension transport is almost non-existent on sand and gravel beaches. On the other hand, the type of sediment transport that dominates the continually subaqueous sand beach type has been widely disputed (Komar 1976a; 214). Admittedly, the patterns of shore-normal sorting on a mixed sand and gravel foreshore show that particle size and shape have major effects on the ways and rates by which material is moved by bedload or saltation, and this problem may be a difficult one to resolve.

The sediment budget of a mixed sand and gravel foreshore is somewhat simplified by the virtual absence of landward transfers both into and out of the system. Because of relative similarity of the foreshore and nearshore granulometrics, it is likely that exchanges between the two zones occur. Also, landward losses from the foreshore by aeolian (wind) transport are high on sand beaches because of the high movability of smaller particles, and the exposure of the upper foreshore during the low tidal phase.

In summary, the wide particle size range that characterises mixed sand and gravel beaches produces a set of distinctive elements that operate and interact in ways that are not typical of other beach types. Comparing such different systems can be done only by reducing them to common components, for which the Process-Response framework provides an appropriate approach. By doing this, it has been shown that the dynamics of mixed sand and gravel beaches are very different to sand beaches. At the same time, it has been suggested that they might also be less complicated.

3.6 CONCLUDING REMARKS

Mixed sand and gravel beaches, which dominate the South Canterbury coastline, provide a relatively new and very different situation for the study of coastal dynamics and beach morphology. The broad size ranges of their constituent materials produce a multifaceted profile form, associated through both cause and effect with an almost coinciding subzonation of other process elements (energy and materials). This is in contrast with the typical sand

beach which, because of the narrow size range of fine and mobile materials, has consistently low surface slopes and a changeable topography with indistinct subzonation.

The different set of environmental process and response elements that occurs on a mixed sand and gravel foreshore has important effects on the transport of beach materials. Clearly, the contrasting process interactions of sandy and mixed beaches produce equally dissimilar sediment transport regimes. The most notable feature of mixed sand and gravel coasts is the dual (nearshore-foreshore) transport system that quite clearly separates the movements of fine and coarse materials alongshore. Within the foreshore itself, the most significant difference between the transport of sediments on sand beaches and on mixed sand and gravel beaches is in the relative dominance of the foreshore subzones.

It is widely recognised that on sand beaches, most of the movement of sediments occurs in the surf zone (Basco, 1982; Komar, 1983), whereas sediment transfers on mixed sand and gravel beaches are dominated by swash zone processes (Kirk, 1980; Muir-Wood, 1970). Contrary to the impression given by the name, and by the comparatively deficient literature on the subject, it has been suggested in this chapter that perhaps in many respects, these and other differences make the mixed sand and gravel beach type the less complicated of the two. Studies on mixed beaches might therefore be potentially more precise and accurate than equivalent studies on sand beaches.

CHAPTER 4

PROCESSES AND PATTERNS OF LONGSHORE MOTION

4.1 INTRODUCTION

The main objective of this chapter is to examine the longshore motions on a mixed sand and gravel foreshore, and to identify the causative processes. Since the interactions of processes on mixed sand and gravel beaches are unlike those occurring on other beach types, it is probable that the processes and patterns of water and sediment motion in the longshore direction are also quite distinctive. Considering the complex three-dimensional nature of the coastal environment, these are unlikely to simply involve a uniform movement of mass along a line parallel to the shoreline. A major problem then, is to discover how it is that wave energy, which tends to enter the beach system approximately normal to the shoreline, tends also to move beach materials parallel to the shoreline in the long term.

The distinctive features of these motions in a mixed beach situation can affect the validity of models and approaches that have been developed for the study of longshore transport on sand beaches. Many may require some adjustments or considerations to be made in order to comply with the processes and patterns that characterise the new situation. A second problem to be addressed here is the applicability of sand beach approaches to the South Canterbury

mixed sand and gravel coast. This chapter will attack aspects of the problem directly, while also establishing a basis for the application in later chapters of sand beach methods for calculating longshore sediment transport rates.

Three types of alongshore transport can be identified on most beaches. These are:

1. longshore energy flux;
2. longshore sediment transport; and
3. longshore translations of morphology.

Each is related to the other two in the ways shown by the Process-Response framework in Figure 1.3. Longshore energy flux manifests itself in the movement of water, since hydraulic inputs are the predominant source of energy on beaches. These are the primary cause of longshore sediment transport, which in turn, can cause the occurrence of longshore translations of beach morphology. Each of the three types of transport will be examined individually in Sections 4.3, 4.4 and 4.6.

This chapter also aims to justify the notion that, because of their different process-response environments, each of the foreshore profile subzones of a mixed sand and gravel beach exhibit distinctly different patterns of water and sediment motion alongshore. Aspects of the subzonation of longshore motion will be introduced throughout the early sections, but will be brought together in Section 4.5 to provide a better view of the interactions of processes that cause movements alongshore.

4.2 LITTORAL ENVIRONMENT OBSERVATIONS

A large amount of the raw data presented in this chapter were collected by staff of the Timaru Harbour Board at a location on South Beach, Timaru, between January 8 and May 14, 1987. This beach is bounded to the north by the seaward-projecting Eastern Extension Mole of Timaru Harbour. The data collection site was 375 m south of this end of the beach. The shoreline at this location faces 112° east of due north, and is completely exposed to offshore waves through 90° to the north of this axis, and 40° to the south. Further around to the south, a submerged basalt reef is present, that can cause large southerly waves to break and dissipate energy before reaching the foreshore at the study site.

The procedure for data collection closely followed that described by the 'Littoral Environment Observation (LEO) Data Collection Program' (Schneider, 1981), which has been developed and widely used on sand beaches in the United States for the purpose of obtaining measurements of coastal phenomena at low cost. Observations were made and recorded once a day at around 2.00 p.m. on 78 occasions throughout the study period. The eight beach variables that were measured on each occasion are listed in Table 4.1, together with their observed ranges. The recording form required for the observations was copied onto plastic sheets to prevent soaking, and is reproduced in Appendix I. The instruction sheet in Appendix II describes the procedure that was followed. Minor adjustments were made to the

Table 4.1 Variables measured in LEO program at South Beach,
Timaru, 8-1-87 to 14-5-87.

Symbol	Description of variable	Range in values	Estimated error range
H_b	Average observed (= significant) breaker height	0.3-1.8m	$\pm 0.1m$
λ_s	Swash length measured from breaker zone to landward swash limit	7-35m	$\pm 2.0m$
T	Average wave period timed over the duration of 11 breakers	3.5-12.6s	$\pm 1.0s$
U	Mean wind velocity - speed - direction	0-15 m.s ⁻¹	± 0.5 m.s ⁻¹ $\pm 23^\circ$
V	Mean velocity of longshore water drift as measured by movement of dye patches over 60s	0-0.967 m.s ⁻¹	± 0.05 m.s
α_b	Angle of wave approach at breakers	0-30 ⁰	$\pm 5^\circ$
β	Surface slope of the upper foreshore face (N.B. surface gradient $m = \tan \beta$)	4-21 ⁰	$\pm 0.5^\circ$
breaker type	Classified as surge, spill, spill/plunge, or plunge		

standard sand beach procedure, to suit the mixed sand and gravel beach situation that occurs at the observation site. The most important of these were the elimination of rip cell circulation and surf zone width observations (since these were absent from the beach) and the inclusion of a swash length estimate.

The data obtained from the program are tabulated in Appendix III. An impression of the range of conditions that were encountered can be gained from a summary description of the LEO data. Perhaps the most significant result to this study is that 62% of the 78 observations recorded wave approach angles within 5° of shore-normal, and only 3% exceeded 25° . The waves approached the shoreline obliquely more often from the southeast quarter, the dominant drift direction (22% of the time) than from the northeast quarter (17%). Overall, the significant wave heights ranged from 0.3 to 1.8 m, with a mean of 0.77 m and a standard deviation of 0.33 m. Virtually all of these waves broke with considerable vertical motion by 'plunging' onto the beach face. No major coastal storms occurred over the duration of the LEO program, so that these data seem to under-represent the higher waves that are known to occur at Timaru (Tierney, 1977). The low-to-moderate energy conditions that were experienced are also reflected in the observed swash lengths, which ranged from 7 m to 35 m, with a mean of 17 m. These values can be compared to the maximum occurring swash length at South Beach, which can be estimated from the distance between the breakers and the storm berm to be about 50 m. It is worth noting that a swash of this length corresponds to a probable maximum breaker height of 3.3 m (from the breaker height-swash length relationships given earlier).

The longshore current measured by the movement of the dye patch was to the north on 50% of the occasions, and to the south 42% of the time. Velocities of the movements to the north reached almost 1 m.s^{-1} , whereas the maximum to the south was only 0.6 m.s^{-1} . Average velocities in both directions were comparable however, being slightly over 0.2 m.s^{-1} .

The average beach slope of 8.8° (1:6.5 gradient), and the range defined by one standard deviation either side of this (5.2° to 12.4°) closely correspond to the typical ranges quoted earlier from Kirk (1980).

Sources of error in the LEO data set similar to those that were noted by Schneider (1981) are likely to be present, but considerable effort was made to reduce these to a minimum. Errors derive mainly from the simple collection methods and the visual estimates of some variables. The probable error ranges for each variable are given in Table 4.1, and are each considered to be reasonably acceptable. Measurements of breaker height, wave direction and swash length were based only on visual sightings, so are probably less reliable than other observations obtained with the help of simple instruments. However, because waves break much further landward and at a more constant position on mixed beaches than on sand beaches, it was found that breaker zone parameters can be estimated with reasonable precision and accuracy. In an attempt to at least maintain consistent levels of error, the observations were made by the same person (Mr. Ray Cox, THB) on most occasions.

4.3 LONGSHORE WATER MOVEMENTS

4.3.1 Causes

Continuous flows of water mass that retain an approximately constant direction for considerable lengths of time (though not necessarily at a constant rate) are collectively known as currents. Coastal currents are not convergent phenomena; rather, they can be produced by a number of different process interactions. Wiegell (1964, in Svendsen and Johnson, 1965; 35) distinguishes between *"currents related to short period waves, tidal currents, currents related to wind action of relatively short duration, and major ocean currents... associated with long duration winds ('climatical')"* Each of these can, and usually do, flow obliquely or parallel to the shoreline, and so produce a longshore movement of water. However, the effect on water motion within the foreshore is unlikely to be significant in some cases, because of the usual nature of water movement into the beach.

Water enters the foreshore zone in a form that approximates to a 'solitary wave' (US Army 1984). The general characteristics of such waves are pictured in Figure 4.1. Unlike deepwater (sinusoidal) waves, solitary wave forms do not exhibit a trough, and they move forward by the horizontal translation of the water mass of which they are composed. In the pure sense, the solitary wave form lies entirely above the stillwater level, and its mass moves independently of nearshore currents. Because the beach surface of a mixed sand and gravel foreshore is predominantly subaerial (above stillwater level), the

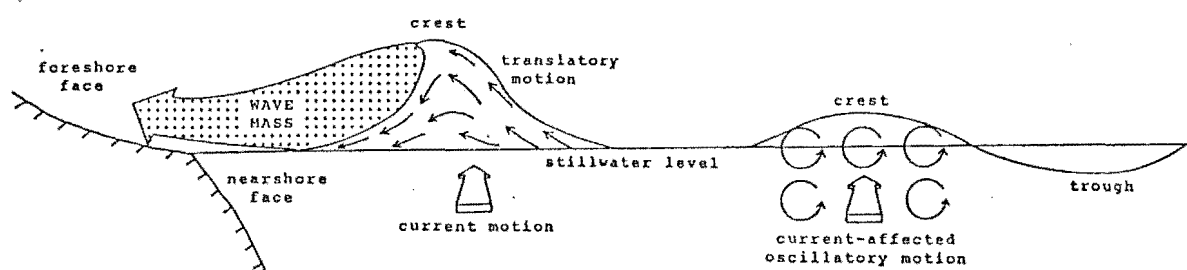


Figure 4.1 A solitary wave near the point of breaking (left) and the deepwater wave from which it developed (right). Note that only the water within the wave form flows onto the foreshore face.

water entering the foreshore must come mostly from the horizontal translation of the solitary wave mass. Consequently, the movement of water within the foreshore is inherited almost solely from the motions of short period (wind) waves, and is little affected by other current-producing processes. Longshore water motions into mixed sand and gravel foreshores are therefore wave-induced and cannot be attributed to ocean currents or tides, though they may have a tidal aspect, through changes in water depth at the toe of the beach producing higher waves at high tide. This conclusion is supported by the graph in Figure 4.2, which shows that the foreshore water mass never flows alongshore in opposition to the direction of wave advance and that it moves at a velocity that tends to increase with the angle of wave incidence.

The movement of water mass along a mixed sand and gravel foreshore is one component of the three-dimensional translation of water by breaking waves and swash. The longshore component is present only when waves approach at an angle to the shoreline. Offshore wave refraction tends to reduce the wave angle, and so also the longshore component of motion. Here it is worth recalling the predominantly shore-normal wave approach that was recorded by the LEO program on South Beach. It is evident from this that translation of water mass perpendicular to the shore dominate the overall motion, and that longshore movements are usually the lesser component.

A point noted by Russell (1960) was that:

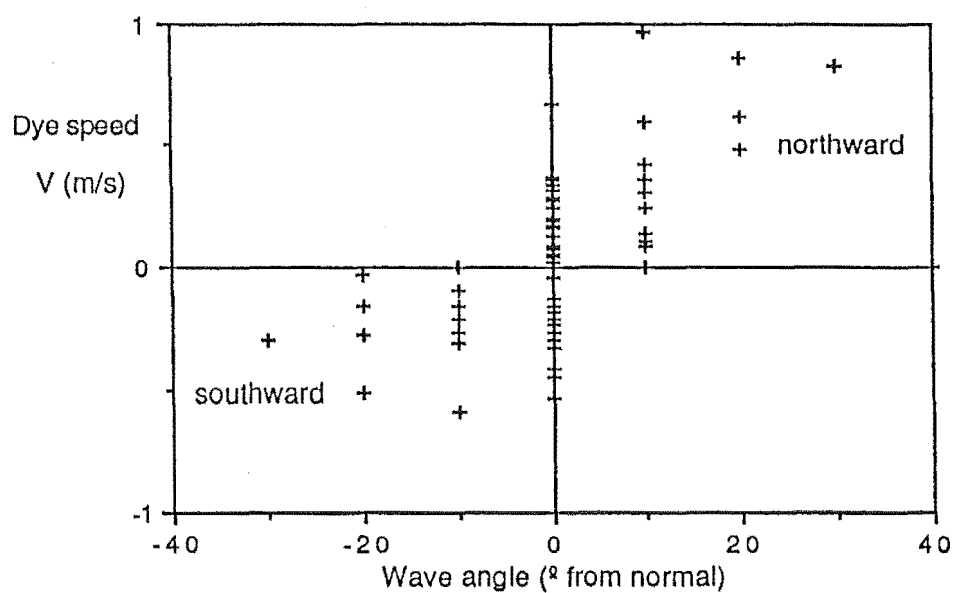


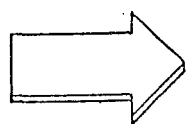
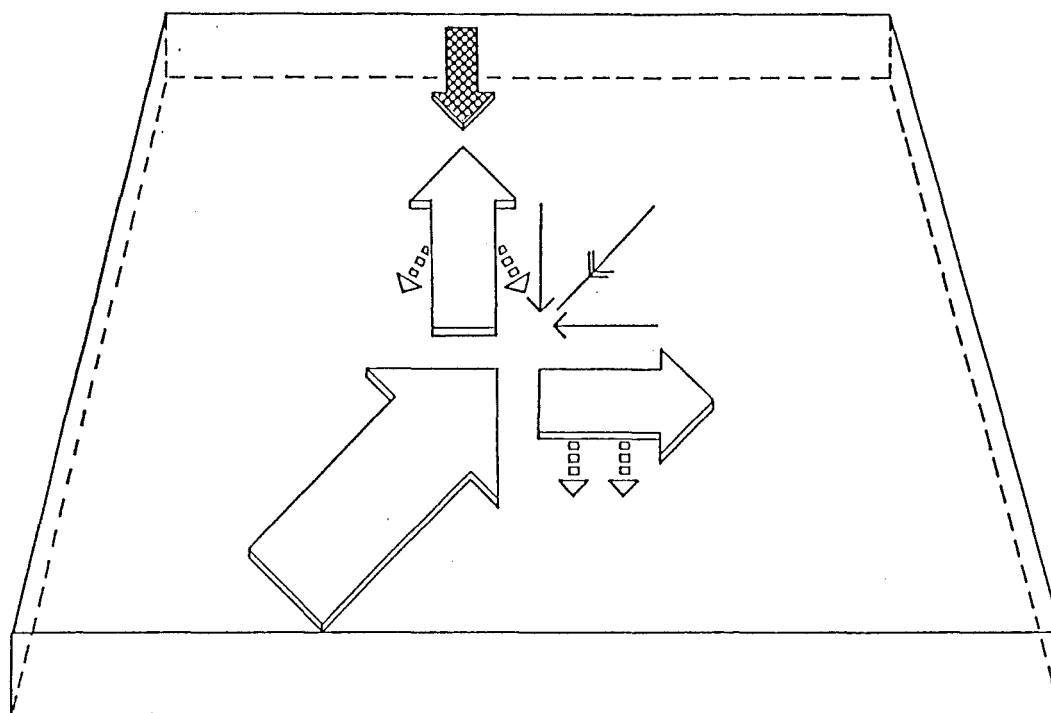
Figure 4.2 Relationship between the angle of wave approach and direction of dye movement.
N = 78.

"On steeper shingle beaches, where waves tend to break close inshore, the movement of the water inshore of the breakers can scarcely be defined as a current, because the water moving up and down the beach in the way that is generally familiar intermittently leaves the beach uncovered."

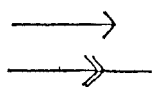
This also applies to mixed sand and gravel beaches, and so reference will be made here not to longshore 'currents', but instead to the longshore mass transport of water, under which currents and oblique wave/swash motions can both be grouped.

4.3.2 Paths of Surface Flow

The regular cycle of water inflows to the foreshore by the propagation of incident waves produces an equally regular cycle of internal flows by breaking waves and swash. Neither the magnitude nor the direction of the incident hydraulic (wave) energy is maintained over the foreshore surface. Three types of processes or forces act to alter and reduce the initial kinetic energy input, and their directional effects are shown in Figure 4.3. The first will be referred to here as 'dissipative processes'. These are energy conversions, caused for example, by friction, noise and turbulence, which may be viewed as reactive forces insomuch as their net or average action is in direct opposition to the direction of flow. Dissipative processes act to reduce both the shore-normal and the alongshore components of kinetic energy. The second type of process is the removal of water mass from the beach surface by vertical percolation. Since energy is a function of mass, this process also reduces surface flows



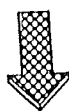
Incident wave energy



Dissipative processes
(opposing)



Percolation
(vertical)



Gravity
(offshore)

Figure 4.3 Forces acting on the incident wave energy within the foreshore.

in all directions. The final process is the action of gravity on the water, operating across the beach surface along lines of the steepest surface gradients. Because beaches tend to conform to a sloping plane that dips seaward, gravity tends to act only on the shore-normal component of water flow. Gravity is thus the only force that operates selectively on the directional components of flow, and the shore-normal component is therefore reduced at a greater rate than the longshore component.

A plan view of the general pattern of water flow velocities parallel to the bed surface, over the duration of a wave period, is drawn in Figure 4.4. The approximate speeds of the flow at points in time and space are indicated by the lengths of the arrows on the diagram, and are given relative to the estimated horizontal speed of the incident wave mass. In accordance with solitary wave theory, the velocity of translation of the wave mass is shown to remain constantly high throughout the wave period (U.S. Army, 1984), but the volume of flow is obviously greatest at the crest and least at the trough. The relative patterns of swash flow that are shown, are based on visual observations and on estimates made by feeling the flow of water around the feet while standing in the swash. Although this qualitative methodology may appear fairly crude, velocities were quite easily compared and simultaneously related to the movements of beach materials underfoot. The main disadvantage of the method was that it restricted observations to relatively low energy conditions. It is not known how well the results can apply to storm conditions.

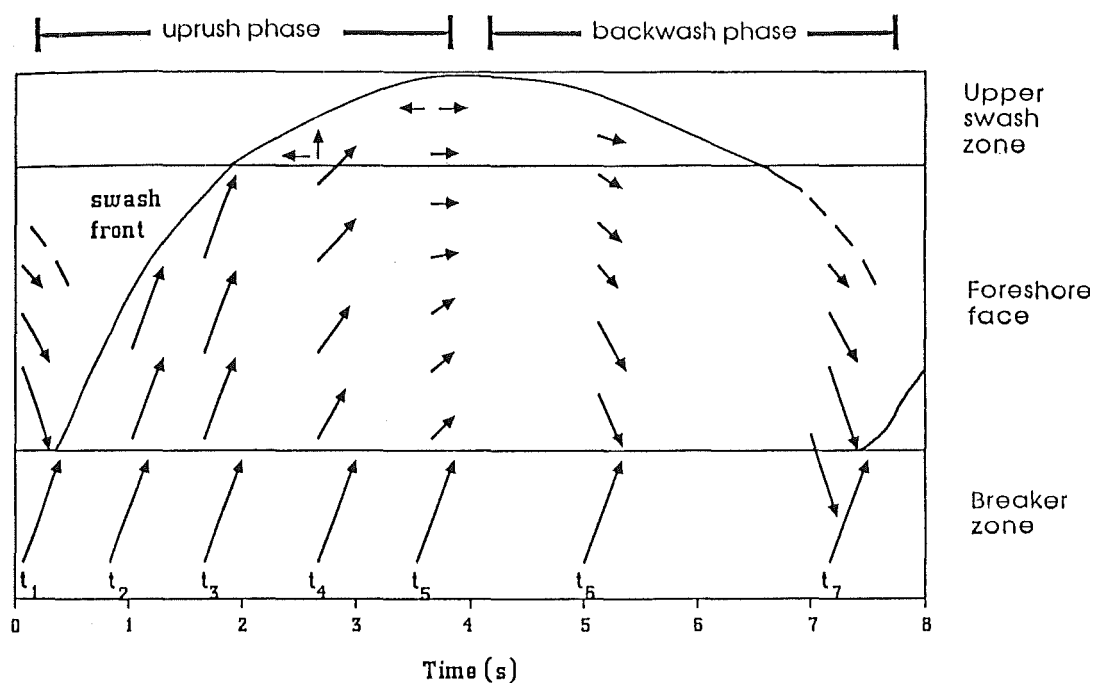


Figure 4.4 Shear velocities over a typical swash cycle, relative to incident wave velocity (plan view). Arrow length indicates magnitude of flow velocity. Times and distances are approximate averages.

Nevertheless, the procedure did allow the acquisition of information on the overall flows of water and not just the progression of the swash front, which is the usual basis of measurement, as used by Dolan and Ferm (1966). It will become evident in this discussion that the swash front is by no means the only region of water motion, and is not necessarily representative of other foreshore flows. It should also be noted that Figure 4.4 shows the movement of the swash front across the foreshore against time, and not against distance alongshore, as most previous studies have plotted. When shown against distance, the swash front water mass traces a 'skewed parabola', resulting from the exponential velocity decrease normal to the shore due to gravity, and the approximately linear decrease in the direction of flow due to dissipative processes.

When a wave breaks obliquely onto the nearshore face (shown at time t_1 in Figure 4.4), high shear velocities and turbulent flows are produced in the breaker zone, having net longshore components comparable with that of the incident wave. Turbulence is increased by the interaction of the opposing backwash from the previous wave. If the backwash flow at this point is considerable, the wave and backwash are 'out of phase' (Kirk, 1970), and the advancing uprush from the broken wave must first overcome the opposing force. Much energy may be used up in doing so, causing a reduction in the length and energy of the swash on the foreshore face. Such an occurrence is a common response to the 'phase difference' of wave and swash periods, and can have a significant influence on the

dynamics of mixed sand and gravel foreshores (Kirk, 1970).

If the uprush is not so constrained, the swash front moves obliquely up the foreshore face at a reasonably high velocity, while the following mass of uprush derived from the decreasing volume of wave input advances as a greater depth of water at a slightly lower velocity (times t_2 and t_3).

Up to time t_3 , the swash direction, and thus the longshore component of direction, remain approximately equal to the incident angle of the wave. As the wave trough and the swash front respectively begin to enter the foreshore and the upper swash zone (at time t_4) the decreasing volume of water then entering the foreshore and the opposing gravitational and dissipative forces cause an overall reduction in the swash velocity. Due to the shore-normal effects of gravity the swash becomes more oblique to the shoreline and the flow of water alongshore begins to assume a greater significance. The onshore flow is completely negated almost simultaneously across the foreshore face at a point in time when the water flow is predominantly parallel to the shore.

At the upper swash zone, the mass of surface water flow is reduced greatly by rapid percolation into the sediment bed, due to the depth of the groundwater table and the large interstitial spaces that are features of this zone. The very low momentum (mass x velocity) of the water in this zone means that the flow can be easily forced by the microtopography or by local hydraulic gradients, so that the swash may disperse in all directions, sometimes in opposition to the angle of incidence (times t_4 and t_5).

On reaching its landward limit, the water begins to return seaward as backwash, accelerating as it progresses (times t_6 and t_7). By this stage, much of the longshore momentum of the flow has been lost to dissipative processes, and the backwash is therefore controlled mostly by gravity, flowing along lines of highest topographic or hydraulic gradients. Towards the final stages of the backwash phase, the remaining water often becomes concentrated into small channels of several centimetres width, so that the flow is no longer as a uniform sheet of water across the foreshore face, but takes the form of discrete rill flows. As the backwash flows through the breaker zone, it may or may not oppose the next advancing breaker in the manner described earlier. This interaction marks the recommencement of the foreshore swash cycle.

It appears then, that the velocity of water flow is greatest in the breaker zone and at the base of the foreshore face. Almost as high are the velocities at the swash front, which are derived from the massive input of water from the breaking wave crest. The longshore flow velocity is reduced throughout the swash period by dissipative activity, and the average mass per unit area of surface flow decreases due to dispersal across and into the foreshore face. In relative terms, however, the component of flow parallel to the shore first increases and then decreases, as the swash turns from uprush to backwash, due to the opposing influence of gravity on the shore-normal flow.

4.3.3 Variability of flow

In addition to the oblique wave approach that causes it, wave-induced water motion alongshore should vary also with other characteristics of the incident waves and with the internal parameters of foreshore energy, sediments and geometry, since these factors are known to affect the movement of water through the foreshore. The nature and magnitude of longshore water motion is controlled by, the overall level of energy input, the longshore component of that input, and the degree to which the energy is utilised and dissipated by other processes. These in turn, are controlled by the action of many process factors.

The overall level of energy input to the foreshore is almost entirely a function of the wave energy. The mass of water flow depends positively on the size (height, length) of the incident wave, whereas the velocity of water translation is inversely related to the wave period. Increases in the energy input by changes in any of these variables should lead to proportionate increases in the shore-normal flow (i.e. swash length) and the mass transport alongshore, as shown in Figure 4.5. The greater longshore displacement is due mainly to the higher velocity, but is also partly due to the longer duration of the swash, since it continues right up to the end of the backwash phase.

The direct influence of wind on the mass transport of water in the foreshore is not likely to be great, since this requires the continuous exposure of a large surface area of water. The frequent removal of water from the foreshore face by backwash denies such an occurrence, while the surface water in the breaker zone is small compared

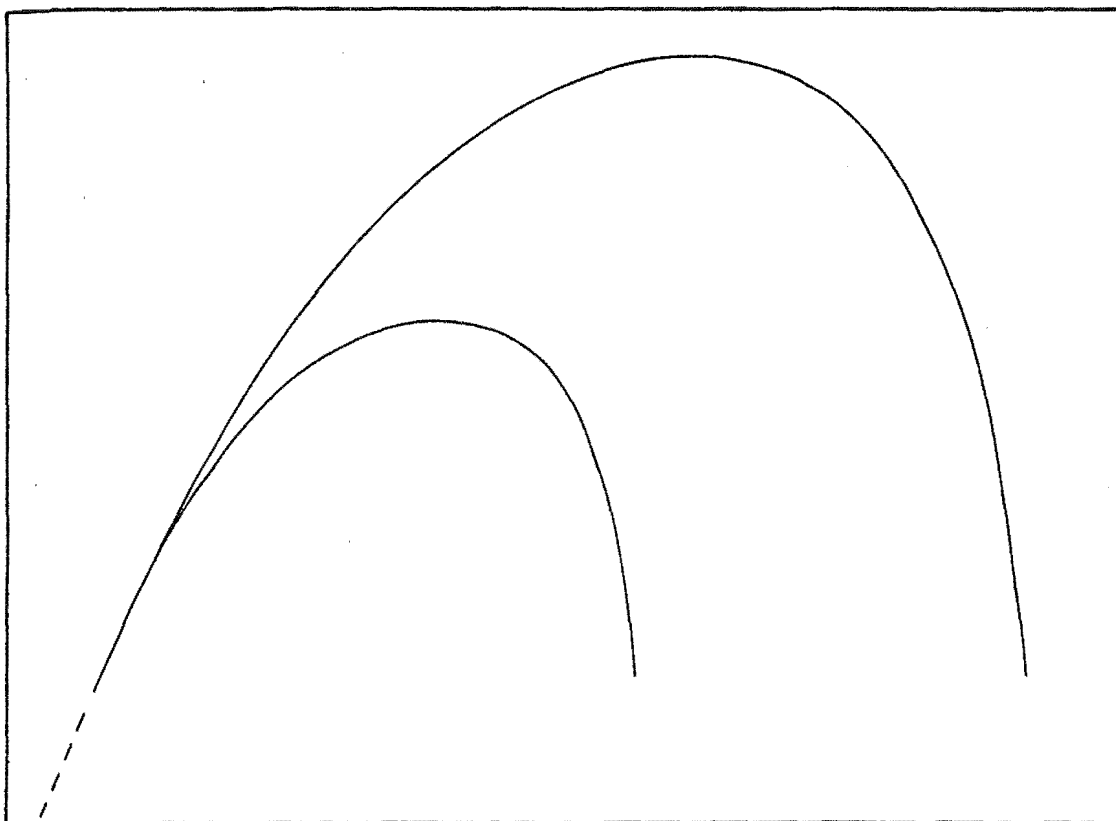


Figure 4.5 The effect of wave energy input on longshore water movement.
- - - incident wave energy
— swash path

with the total volume, and is dominated by wave motion. Only small amounts of kinetic energy can therefore be transferred to the foreshore water surface by winds.

The component of the energy input that is directed alongshore is primarily attributable to the magnitude of the wave approach angle, since this has an obvious effect on the relative significance of flows normal to and parallel to the shore. Figure 4.6 shows that the maximum distance of swash flow alongshore is produced by moderately high wave angles. Low wave angles may have long swash paths, but only a small component of longshore movement, whereas very high angles produce a very large longshore component, but quite short swash paths. Angles approaching or greater than the optimum for longshore motion by swash seldom occur on open coast beaches because of refraction.

From the principles of conservation of energy, the kinetic energy of water can only be equal to that not used up by other processes. The dissipation of energy within the foreshore thus reduces the amount available for the longshore mass transport of water. For example, when breaking waves 'plunge' with pronounced vertical motion and much noise, less energy remains to generate horizontal motion, and the longshore movement is diminished as a result. In a similar manner, the removal of water mass from the foreshore surface by percolation and offshore swash retreat reduces the volume of water flowing across the beach, effecting changes to the patterns and rates of flow.

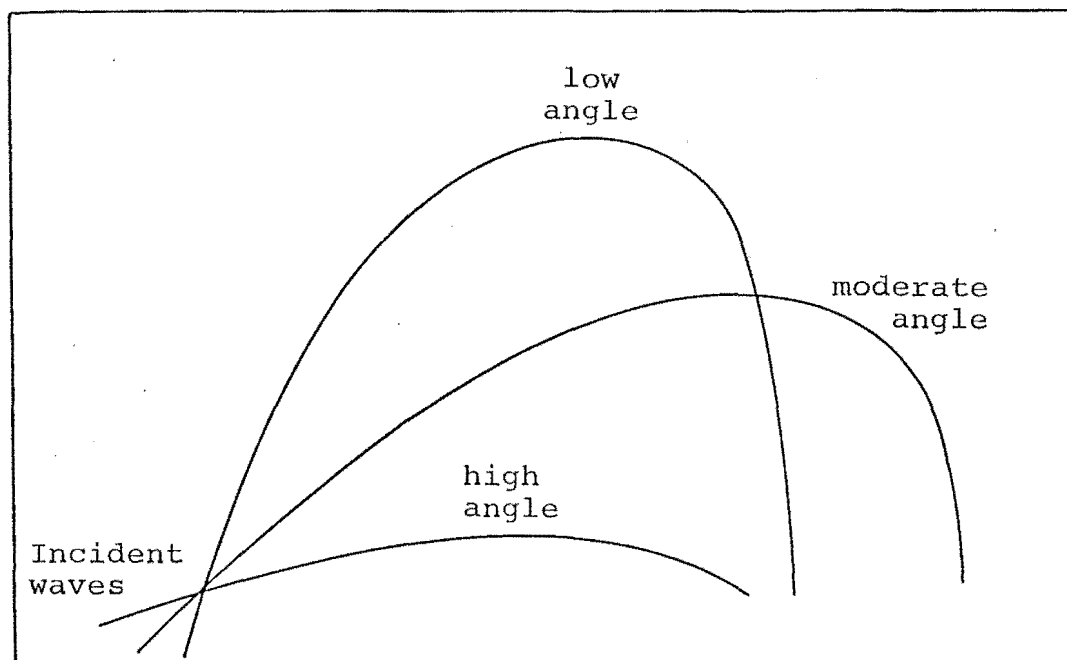


Figure 4.6 The effect of wave angle on longshore water movement.

4.3.4 Dye Tracing Analysis

Dye tracing of water flow is a simple method for measuring the longshore motion of water over short periods of time. The importance of currents to the suspended transport of fine grained sediments is known to be high, so an ability to predict and interpret the nature and velocity of the longshore current on a sand beach is of considerable benefit to the study of longshore sediment transport. Consequently, an extensive body of literature studying longshore currents on sand beaches has appeared since 1949, when Putnam et al. published a paper on the prediction of current velocities. The usual approach to understanding longshore currents has been by the correlation of measured flow velocities to a variety of coastal phenomena. Komar (1983) gives a comprehensive review of recent studies on the topic.

Dye tracing was undertaken on a daily basis as part of the LEO program at South Beach, with simultaneous measurements of other beach variables. A volume of 300 ml of methylene blue dye was used each time, and was injected just inshore of the breakers, using a can thrown out on the end of a string. The centre of the dye patch was then followed alongshore for one minute, and the distance travelled was paced out (in metres). This method has been widely used in previous longshore current experiments.

The methodology for measuring and interpreting mass transport of water by dye tracing has not been investigated in the literature to date for mixed sand and gravel beaches. The data collected in the LEO program on South Beach provides a very good base to start such a

study. Thus, the primary aim of this section is to search for a statistical relationship between the rate of dye movement along the beach, and a number of other variables, and then to examine how well the relationships reflect the mass movement of water as described in the previous section.

Linear regression analysis was performed on the observed dye speeds (V , m.s^{-1}) and six other beach variables: the longshore component of wave approach per unit length of beach ($\sin 2 \alpha_b$), mean wind velocity alongshore ($U_\ell = U \sin \alpha_{\text{wind}}$, m.s^{-1}), significant breaker height (H_b , m), wave period (T , s), swash length (ℓ_s , m), and foreshore gradient ($m = y/x$). The first two of these six variables were considered only in relation to the direction of dye movement, since the actual directions ('left' or 'right') should have no effect on the speed of movement.

The scatter diagrams and linear regression coefficients (r) presented in Figure 4.7 compare the observed dye speeds with the concurrent observations of the other six variables. The strongest linear relationships can be seen to be with the longshore component of wind velocity, the angle of wave approach, and the breaker height. Each of these were positively, though not particularly strongly correlated to the dye speed. The most logical reasons for these results, if they can be taken as truly representative, are that the rate of mass transport alongshore is controlled mostly by the overall level of energy input (breaker height and absolute wind speed), and also by the longshore component of the energy flux (wind direction and wave approach).

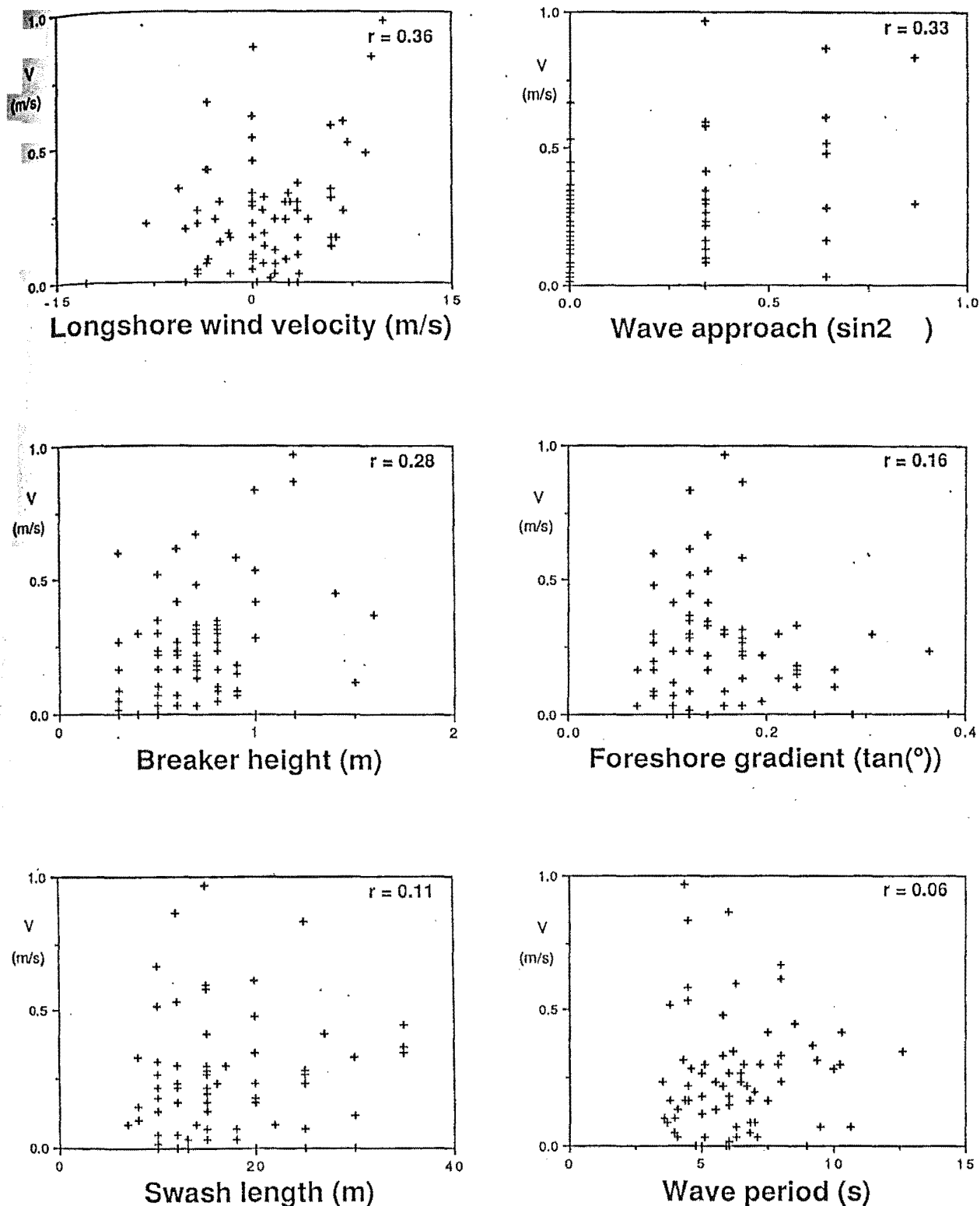


Figure 4.7 Relationships between dye speed (V) and other beach variables. $N=78$. Note the wide scatter and low linear regression coefficients in every case.

Because of the poor correlations, no single variable (of those analysed) can be used to suitably describe the speed of dye movement statistically. Furthermore, it was found that predictive equations derived for longshore currents on sand beaches (Galvin, 1967; Longuet-Higgins, 1970; Komar, 1983) grossly overestimated the actual dye speed when applied to the sand and gravel beach conditions. The discrepancy was not just of magnitude however, as a poor correlation to the variables existed in each case. It is evident from this, that because of the different processes acting on sandy and mixed beaches, equal changes in beach variables will produce very different changes in the dye speeds on the two beach types. A completely new equation is therefore required to model the mixed beach situation.

In an attempt to find a simple, but more precise expression for the prediction of dye speed (Y , the predictand), a stepwise multiple linear regression procedure was applied to the other six variables (X , the predictors). The procedure, described by Harrison et al. (1965), is to begin by selecting that predictor that makes the largest contribution to explained variance and then to successively select the predictor that contributes most to reducing the residual of the preceding regression equation. The addition of predictors to the equation is discontinued when the amount of improvement attained at each step is found, by F ratios, not to be significant. Snedecor and Cochran (1980) suggest the use of a constant value of $F_{crit} = 3$ for this procedure, which is close to

the 5% significance levels for each of the steps in the present exercise. The final result is an expression of Y as a linear function of a number of X_n ($n = 1, \dots, N$).

Thus,

$$Y = A_0 + A_1X_1 + A_2X_2 + \dots A_nX_n \quad \dots (4.1)$$

where the coefficients A_n are determined using the least squares method.

Applying this procedure to the LEO data, the results given in Table 4.2 were obtained. It can be seen that the improvement attained became no longer significant at the fourth step of the procedure. Therefore, only the first three of the six predictors considered here had a significant influence on the accuracy of the dye speed prediction.

The results of the analysis indicate that the wind appears to have the most significance in the mass transport of water alongshore. Following this, only the wave approach angle and the breaker height were found to also have a significant influence. The three other variables that were considered did not contribute to a significant variance reduction at the 0.95 level. It was thereby found that the simplest, reasonably accurate prediction for the dye speed can be made by applying the equation

$$V = 0.062 + 0.011U_{\ell} + 0.236 \sin \alpha_b + 0.189 H_b \dots m.s^{-1} \quad \dots (4.2)$$

In concordance with Harrison et al. (1965), this estimated value for the longshore water drift does not distinguish the direction of movement, but only the rate of displacement alongshore, away from the point of dye injection. If the

Table 4.2 Selection of predictors for V by stepwise
screening process (N = 72)

Step	Variable	r^2	Partial F of variable on inclusion into the equation	Significant improvement ? $F_{crit.} = 3$ (at $\approx 5\%$ level)
1	U_ℓ	0.131	10.51	
2	$\sin 2 \alpha_b$	0.188	4.89	Yes
3	H_b	0.246	5.20	Yes
4	T	0.270	2.24	No
5	ℓ_s	0.285	1.37	No
6	m	0.299	2.15	No

direction is also to be specified, this can be accurately obtained from the direction of wave propagation, which was shown earlier to have a direct control on the direction of dye movement. In Figure 4.8, the observed dye speeds are plotted against their predicted values calculated from simultaneous LEO observations, using this equation. Several aspects of these results are worthy of notice.

It can be seen that only 25% of the total variance ($R^2 = 0.246$) of the predictand, V , is explained by the three predictors in Equation 4.2. Although this is an improvement on the use of just one predictor, highly significant residuals still remain. Two main causes for this inaccuracy are likely to exist, apart from the measurement errors that were discussed earlier. The first is the limited number of predictors that were used in the regression analysis. Many other factors and interactions occur also, to produce the observed dye movement. The six used in this analysis were chosen mainly for their ease of measurement, and are by no means necessarily the most influential in terms of flow forcing. The second source of inaccuracy is in use of linear analysis. Some variables that have only a small linear effect may still have a strong influence on the dye speed. This can be noticed in the graph comparing the foreshore gradient and dye speed in Figure 4.7: it appears that high gradients impose an upper limit on the current speed, since steep faces ($>1:5.5$) and high dye speeds ($<0.3 \text{ m.s}^{-1}$) were each recorded 25% of the time in the LEO program, but they never occurred together. Such a relationship, if valid, cannot

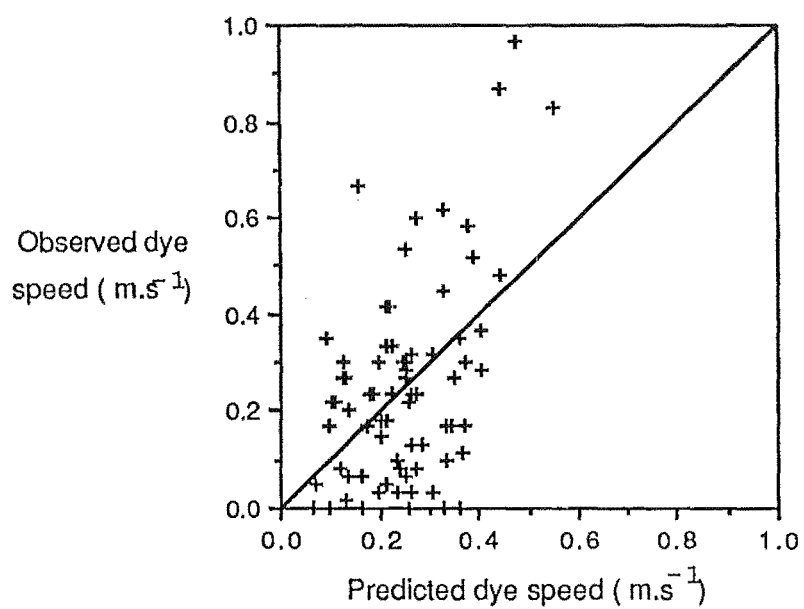


Figure 4.8 Predicted vs observed values for water dye movement alongshore (predicted values obtained using Equation 4.2).

be expressed by a linear function, and so was not adequately recognised in the analysis. Despite this problem, Harrison et al. (1965) note that "it is also true...that the linear model is generally the best one for initial work."

The most surprising aspect of the results is the indication that the wind appears to have the most significance in the mass transport of water alongshore. This conflicts with the physical reasoning given earlier for the unlikely importance of wind on mixed sand and gravel foreshores. Bearing in mind the complete control of the wave approach on the direction of dye movement, no adequate reason can be given for this apparent dominance of wind over water. It should therefore be noted here, as it has been elsewhere (e.g. Harrison et al, 1965; Komar 1976a; 197), that statistical correlation alone does not necessarily signify physical cause and effect, but merely indicates which parameters appear to have the most significance.

A further point of interest in the results of this study is the very low significance of parameters that directly describe the foreshore face (ℓ_s and m), compared with the breaker zone parameters (α_b , H_b and T). Although a considerable amount of water movement occurs across the foreshore face as swash flow, it does not appear to be well represented by the predicted value for the dye speed. A likely reason for this lies in the fact that it is the most concentrated (i.e. clearest) patch of dye that is followed by the tracing method, and so the effects of processes that tend to disperse the water volume over a wide area are not included in the measurement of dye

displacement. Swash flows are very dispersive, and also cause the removal of dyed water from sight by percolation. The least dispersive flows occur at the base of the foreshore, where water movement is only partially affected by the translation of the solitary wave mass into swash. On the six occasions that the dye patch was lost in under one minute, the dispersal was unlikely to be alongshore due to the wave angles, which were mostly zero, but more probably it occurred across the foreshore due to the very long swash lengths (>25 m). It is therefore probable that dye tracing methods record only the movement of the water that remains near the breaker zone, and may not represent the total water motion. This suggestion is well supported by observations of the dye patch itself, namely, that it did not move up and down the foreshore with the swash, and although it remained within the breaker zone, it was rapidly dispersed and became untraceable within several minutes.

In summary, the dye tracing method for measuring longshore water movements on a mixed sand and gravel beach seems to be a very reliable indicator of the direction of wave approach, but it does not appear to represent the movement of all types of internal foreshore water flows. Predictions of the dye patch velocity from concurrent, easily measured beach variables can only account for about one-quarter of the observed variance, and may contain some spurious correlations (for example, with longshore wind velocity). More accurate predictions may be made possible by the inclusion of more variables and more data, and should be made with some consideration

of the physical processes that are known to affect the dye patch movement.

4.4 LONGSHORE SEDIMENT TRANSPORT

It is known that beach materials are moved alongshore by the actions of waves that arrive obliquely at a coastline. Those hydraulic actions were discussed in the last section. Also controlling the movement of beach materials are the characteristics and movability of the sediments themselves. Particles of different shapes and sizes are moved along a mixed sand and gravel foreshore in different ways that are far from easy to understand. The paths of sediment movement do not simply trace the swash paths, and the rate of particle movement alongshore is not just a simple matter of longshore size-grading. These two factors - the paths and rates of particle movement by waves and swash - are the focus of this section.

4.4.1 The Boundary Layers of Sediment Motion

The water movements at, and very near (above and below) the bed surface are the most important to the movement of particles on a sand and gravel foreshore. In general, sediments do not usually move in the foreshore outside of this boundary layer, and almost never do so continuously for longer than a single wave/swash period. Above the bed surface, the boundary layer is confined by the ability of the water turbulence to carry particles into suspension. Under the normally occurring light-to-moderate swash conditions, this ability extends no higher than about 3-4 cm from the surface of a mixed sand and gravel beach. In the

breaker zone however, and probably during storms, the high levels of vertical mixing by plunging waves and high energy swash can raise the finer particles to heights that are limited only by the water depth. It is therefore not so much the volume of flow, than the effectiveness of the boundary layer flow, that is important to the transport of coarse material.

Below the bed surface, the sediment can be displaced if the energy of the flowing water penetrates vertically into the foreshore, or if the overlying particles are removed by the flow. The depth to which materials are able to be displaced by hydraulic forces is commonly known as the 'depth of disturbance', and the volume of sediment above this depth is the 'active layer'. These parameters are known to be very important to the rate of longshore sediment transport, because they define the thickness of the layer of material set in motion. Unfortunately, they have also been found to be very difficult to measure and interpret. The main problem is in the time scale over which they should be measured. In general, the volume of the active layer increases along with the time scale used. Three time scales of the coastal environment can be conveniently identified; the swash cycle, the tidal period, and the event period. The depths of disturbance at each are relevant to the study of longshore transport, the first and last being of special importance to the present study.

Swash cycle depth of disturbance

Zenkovich (1967; 360) asserts that the depth of disturbance over a single swash cycle is of the greatest

importance to the calculation of longshore sediment transport rates, but adds that measurements at this scale are hard to obtain, because of the difficulty of carrying out such work in the surf zone. Many problems arise in developing a suitable methodology, particularly on mixed sand and gravel beaches. For example, relevant results from the 'tracer plug' method described in a previous chapter must use a plug that closely represents the vertical structure of the bed into which it is inserted. In a mixed sand and gravel beach, the vertical structure of particles is known to be complex and to contain a wide range of particle sizes and shapes so that it is almost impossible to replicate in a tracer plug. Only the foreshore face exhibits a homogeneous surface layer that is sufficiently deep for the tracer plug method to be found at all useful. Here, there is a layer of coarse sands and fine gravels usually extending to a depth of about 20 cm. It is thought that this layer itself represents the depth to which the bed is usually disturbed over a tidal cycle, since it is vertically constant, and is underlain by coarse particles that may have been deposited by the lower swash at high tide.

Two experiments were undertaken on South Beach to estimate the depth of disturbance of the foreshore face by a single swash cycle. The first involved the rapid insertion of a tracer plug following the backwash of a wave, and the equally rapid recovery after the following swash cycle. The plugs were approximately 3 cm in diameter and 15 cm long, and were comprised of a representative grain size distribution marked with spray paint. They were inserted vertically into the face by the placement of a tracer-filled, transparent corer onto a small metal plate at the bottom

of an excavated hollow. The hollow was then refilled and the corer withdrawn, leaving the tracer plug in situ. In spite of the short time available for insertion, the procedure was satisfactorily followed and care was taken to ensure that the top of the plug was flush with the bed surface.

Since the top of the plug was invariably replaced by native beach materials, its location had to be marked to allow recovery. Physical markers, such as stakes, were unsuitable because they affected the local flow patterns, and so also the depth of disturbance. Therefore, in this experiment, the location was marked visually over the duration of the swash. This usually allowed the plug to be accurately relocated, but did not allow time for observations of hydraulic parameters (wave height, swash length, etc.).

After the passage of the uprush and backwash following plug insertion, the corer was reinserted to recover the plug. The measured changes in the overall core length and in the tracer plug length, allowed the maximum depth of disturbance and the net surface level change to be calculated, as shown in Figure 4.9.

The major problem with this method is that the disturbance of the sediment bed during the insertion of the plug is quite likely to have an effect on the depth of disturbance by swash. The natural bed is structurally ordered and the particles lie oriented along axes of flow. Percolation, and the depth of disturbance, is greatly influenced by the matrix structure, and so it is altered by the experimental methodology used to measure it.

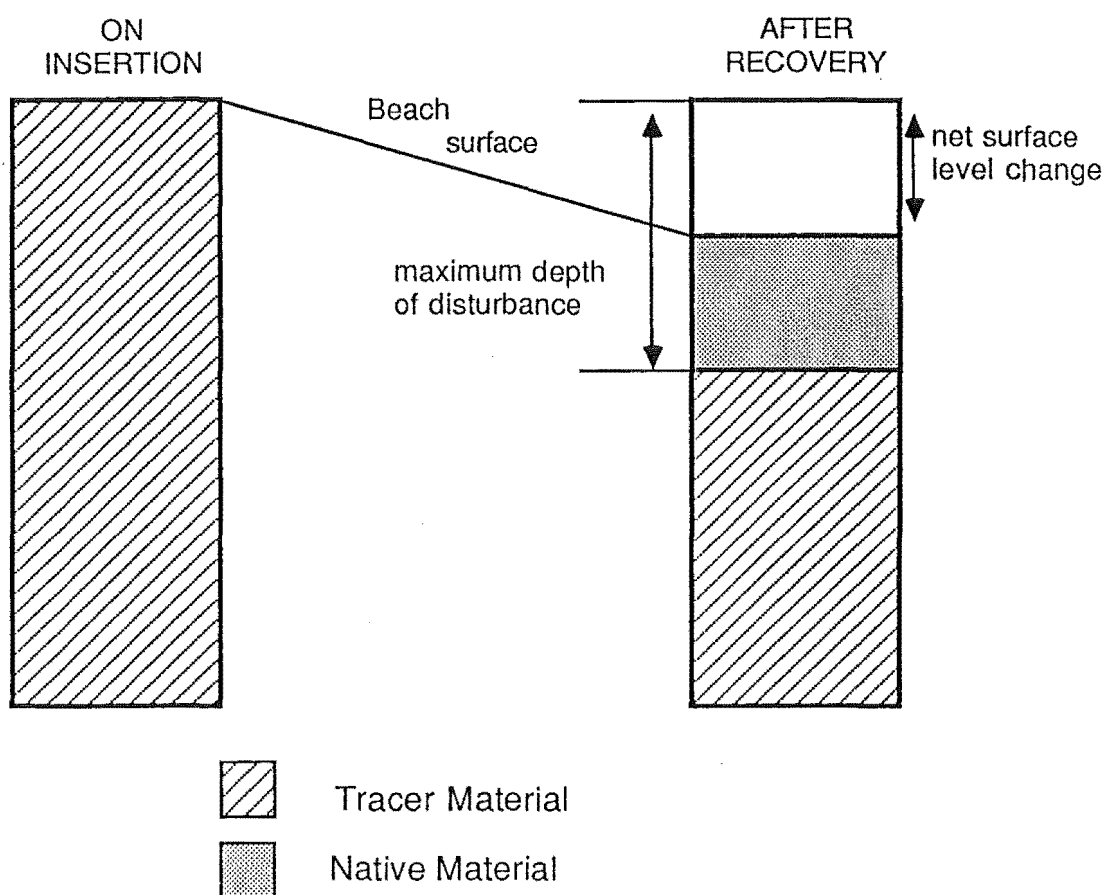


Figure 4.9 Tracer plug changes over a swash cycle.

To overcome this problem, a second method was tested that measures the depth of disturbance of the native material without greatly disturbing the bed itself. This involved simply, the application of a light downward pressure of a narrow wooden ruler onto the bed surface during the passage of a swash flow. The ruler was aligned to face roughly parallel to the flow, so that movements of neither water nor materials were significantly affected by it. On the assumption that the ruler is pushed down into spaces made vacant by moving particles, the depth of disturbance can be measured directly. The downward pressure applied to the ruler was maintained reasonably constant, at a level that was found prior to swash advance to be not quite sufficient to force the ruler into the stationary bed. This helped to ensure that the downward pressure was not causing the displacement of the bed particles. The general method, although more simple than the tracer plug method, is thought to be also more flexible and accurate. The flexibility derives mainly from the fact that the procedure can be commenced or ended underwater.

The results from the two experiments were quite comparable. They both produced consistent estimates for the depth of disturbance by a single swash cycle of 30 ± 5 mm. The measurements were repeated a number of times, but are representative only of a mid-foreshore face composed of fine gravel under the swash of 0.8 m high waves. Further experiments could produce a better indication of the variability of the active layer under changing conditions.

The tracer plug experiments showed that little if any net change occurs to the beach surface level over a swash cycle, so that particle movements at depth are more likely to be due to water percolation and energy penetration than to their exposure by the removal of surface materials. The second method permitted the commencement and/or ending of measurements to be made part way through the swash cycle, thus enabling the depth of disturbance by each phase to be measured. The results of this procedure showed that particles were moved at the maximum depth during the uprush phase, and were moved to depths of only 20-25 mm during the backwash. This difference is likely to be related to the fact that backwash velocities are lower as were observed and measured by Kirk (1970).

It seems then, that the passage of one wave/swash cycle across a mixed sand and gravel foreshore sets in motion a layer of material that is several particle grains deep. When the wave direction is oblique to the shoreline, all of the particles within this layer are moved alongshore. Since the maximum swash velocities and the grain sizes are approximately equal across the foreshore face, it is plausible that the depth of disturbance is also. The depth of disturbance in other zones is more difficult to evaluate. However, because the foreshore face constitutes a high proportion of the active surface area of the mid-foreshore, a reasonable value for the overall average depth of disturbance would be the depth measured in the foreshore face. Under the moderate wave conditions studied here, with a 3 cm depth of disturbance, and a swash length (active beach width) of 20 m, it is estimated that 0.6 m^3 of material per metre of

beach length is moved alongshore at some stage over a swash cycle.

Event Period depth of disturbance

The depth to which foreshore materials are disturbed over the duration of a storm or swell event is very much different to the swash cycle depth of disturbance, in terms of both cause and magnitude. Throughout such events, sediments are redistributed across and along the shore, and the surface morphology changes. By this means, sediments buried to depths of metres, rather than centimetres, may become exposed and subjected to the hydraulic forces. The influence of percolating water on the depth of disturbance becomes almost insignificant, and the active layer can be measured with sufficient accuracy from beach profile data showing the changing level of the beach surface.

This method was used to determine the cross-sectional area of the active layer of the foreshore that is moved alongshore during storm events at South Beach, Timaru. Data were obtained from beach profiles made by Timaru Harbour Board (THB Sheets 94-1, 2 and 3, Sections A and B) along two lines between 1979 and 1982. Fourteen profiles were taken on each line, at approximately two-monthly intervals. The profile lines are quite close to the breakwater end of the beach (375 m and 600 m respectively), but are not so close as to be affected by hydraulic effects such as reflection off the breakwater itself. The changes in the total volume of beach sediment at these two locations were found by measuring the net changes in the cross-

sectional area beneath the surface profiles, and above mean sea level. To achieve the aim of the exercise, i.e. to estimate the active layer of material being moved alongshore, the assumption had to be made that all volume changes are totally due to longshore drift in one direction. This is justified by the statement made earlier, that short-term transfers through the landward and seaward boundaries of a mixed sand and gravel foreshore are minimal. In addition, the adjacency of the breakwater to the north of the lines means that sediment supply from this direction is relatively low. Most of the volume change to the beach at the profile lines is therefore due to movements alongshore from the south.

The maximum short-term (two-monthly) net gain in the profile envelope should provide the best available estimate for the active beach volume, for two reasons. Firstly, gains are better measures of longshore drift than losses, since offshore transfers favour losses by attrition and alongshore losses to the north may sometimes be held up by the presence of the breakwater. Secondly, the maximum value is the best one to use, since it is the closest to the true value. The active layer must equal or exceed it, but clearly profile surveys may not coincide with times of maximum accretion and/or erosion.

It could reasonably be argued that the interval of two months between surveys does not accurately represent the duration of a storm event. Most coastal storm events on the South Canterbury coastline are linked to meteorological conditions that endure for only a few days. Within a two-month period, it is conceivable that several storms could

occur in succession, possibly having a cumulative effect on the beach volume. If this happens, the volume of inter-survey profile change no longer represents a single storm. Ideally, an accurate estimate of the active layer would require surveys to be made immediately before, during and after a storm. Unfortunately, the difficulties that this involves means that such data are not available, and so the two-month periods that have been covered are the most suitable and are assumed here to encompass no more than one storm event each.

The maximum two-monthly gains over the period surveyed were found to be 37.75 m^2 and 54.75 m^2 at Profiles A and B, respectively. To gain a measure that more accurately represents the active layer of the entire beach, the average of these two values (46.25 m^2) will be considered. This value represents the volume (cross sectional area times the length of beach) of material that is set in motion by a storm event. Since storms dominate the longshore movements of material, due to their high levels of energy (and their oblique wave approach on the South Canterbury coast), it is this active storm layer that is the most significant and accurate measure of the depth of disturbance for studying the rates of long-term sediment movements along a beach.

4.4.2 Paths of movement

Foreshore materials can only move in the direction of the forces that act on them. It is therefore quite certain that the longshore movements of sediments are closely related to the wave and swash flows. However, periodic

deposition and non-entrainment occurs as a result of the regular presence of low hydraulic shear velocities. The movements are therefore not continuous nor at the same rate as the water flow, and so do not describe the paths of water movement exactly.

Many authors (e.g. Palmer, 1834; Johnson, 1919; Zenkovich, 1967) have surmised or attempted to observe the paths traversed by coarse materials, and the consequential magnitude of longshore displacement. Most have logically concluded that coarse sands and gravels are "pushed and rolled across the beach face, tracing a saw-tooth path in the direction of wave travel," (Gibb and Adams, 1982). Such a pattern of movement is shown in Figure 4.10. It is produced by the entrainment and transport of the material by an oblique uprush, the momentary deposition as the shear velocity falls below a critical level due to dissipative processes, and the re-entrainment as the critical velocity is again exceeded by the accelerating backwash. Thus, the paths of particle movement across the foreshore are truncations of the 'skewed parabola' that is characteristic of the swash flow.

From the diagram in Figure 4.4, it was seen that the swash velocities change progressively but rapidly across the foreshore over time. Particles are entrained and deposited frequently, at times when the shear velocities cross the critical levels for sediment transport. They remain mobile, and so move alongshore, only while these thresholds are exceeded. Because granulometry is a controlling factor of the critical velocities of motion, the observed swash velocities can be replaced by measures of

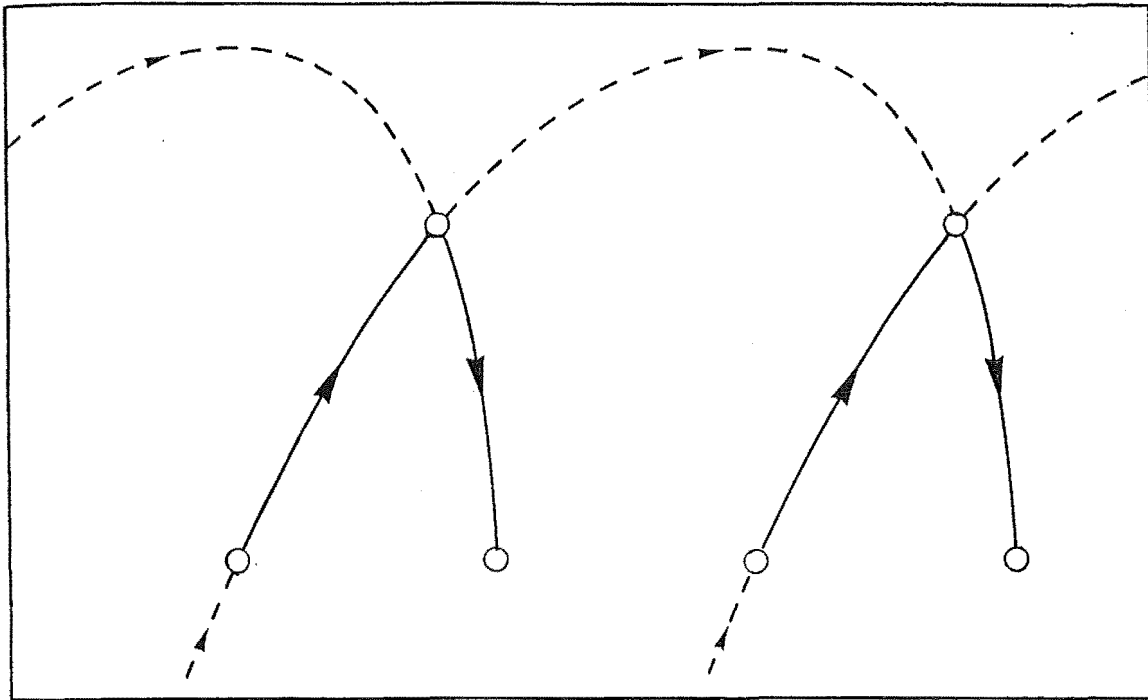
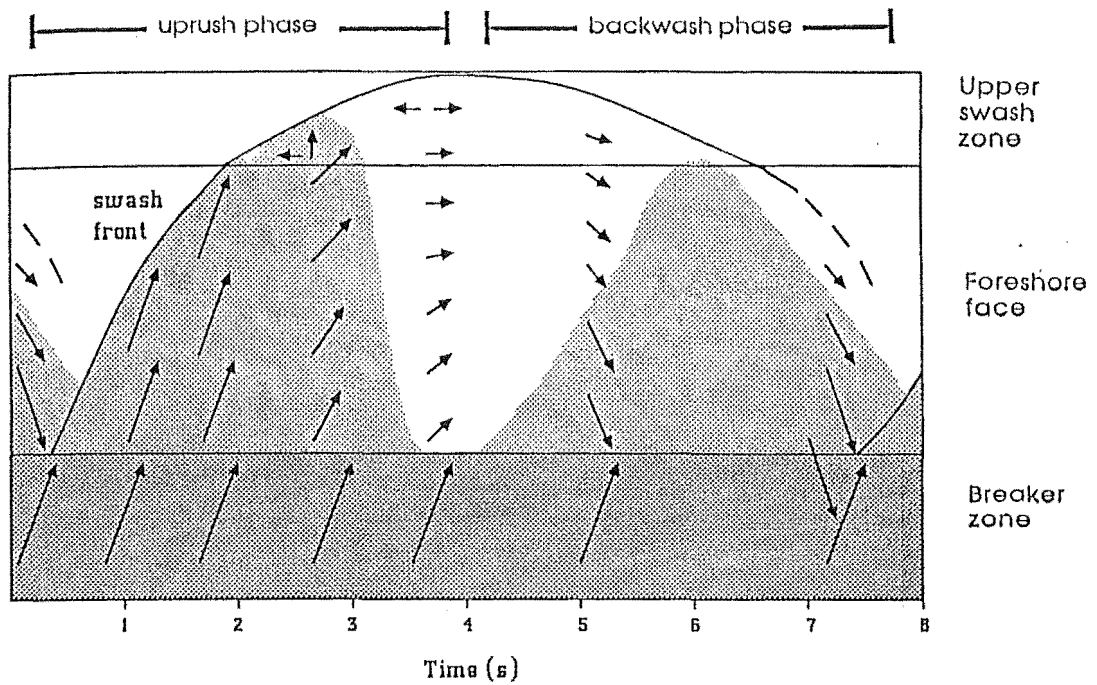


Figure 4.10 The path of particle movement caused by swash.
--- water movement
— particle movement

their ability to move surface particles of different shapes and sizes, and this has been done in Figure 4.11.

The diagram is calibrated on the basis of observed occurrences of sediment motion on South Beach that were made simultaneously with the water flow observations described earlier. The motion of the in situ material could be seen, heard and felt as the waves and swash moved across the foreshore. The durations of motion were timed at several points on the foreshore, and approximate averages were taken to provide a basis for the results shown. Superimposed on the directions and velocities of water flow, the diagram presents the times and locations at which sediments of different sizes can (if present) be moved, throughout the swash cycle. The presence or absence of certain particle sizes is an extremely important consideration to be made, since the water flow can only act on the particles that are present at the surface, or within the active layer.

Two major conclusions related to longshore sediment transport can be drawn on the basis of this diagram; the first concerns the effects of particle size and shape on the paths of motion, and the second has to do with the spatial distribution of sediment transport across the foreshore. It can be seen that finer (more movable) particles can be kept in motion for a longer duration than less movable particles. Once entrained, the length of movement is reliant on the non-deposition of the particle. Less movable particles are deposited more rapidly in the falling velocities of the advancing uprush, and so are likely to be moved alongshore at a lesser rate than more mobile particles moving from the same location. It also appears that most of







-  Easily transports most particles
-  Easily transports small particles and some coarse (spherical)
-  Sufficient to entrain small particles
-  Insufficient to entrain any particles, deposits all moving particles

Figure 4.11 Typical motions of surface particles over a swash cycle (plan view).

the potential for movement of material on the beach surface by high shear velocities (as indicated by darker shading) occurs towards the base of the foreshore, and near the beginning and end of the uprush-backwash cycle.

The combination of these and other factors helps to complicate the actual pattern of sediment transport. The problem of process interactions causing responses that cannot be predicted solely from a knowledge of discrete process elements (energy, materials, geometry) was introduced in the previous chapter describing mixed sand and gravel beaches. The situation was partly overcome by viewing the beach as a set of separate, but related, process sub-systems. The problem continues here, in the study of long-shore sediment transport patterns, so an examination of the subzonation of longshore motion seems the appropriate solution.

4.5 THE SUBZONES OF LONGSHORE MOTION

It is well known that the mixed sand and gravel coasts of South Canterbury are characterised by two major zones of longshore motion and sediment transport; the near-shore zone and the foreshore zone (Kirk, 1980; Gibb and Adams, 1982). The current-induced transport of the sediments across the deep shelf of the first zone contrasts with the transport of gravels and sands in the second zone as beach drift by the action of broken waves. These zones are distinctly separate, and are characterised by very different process-response systems and sediment budgets.

Less frequently considered is the possibility that the patterns of longshore motion are similarly zonated

within the foreshore. It was shown in the previous chapter that the foreshore can be divided into five subzones with different process environments between which sediment transfers occur at a significant scale only when the process elements are thrown into disequilibrium, for example, by a change in the level of wave energy inputs. Therefore, when beach materials are acted upon by an oblique, but constant wave field, it may be supposed that they are moved alongshore while remaining predominantly within the same subzone.

Consider, for example, a case in which the incident wave field is uniform over time. The five subzones will remain in a constant dynamic equilibrium condition with respect to energy, materials, and geometry. Provided the subzones are separated by reasonably abrupt process changes, each particle will remain within the same subzone. Particles in one subzone cannot be transported, or will not be deposited, by the process interactions in another and so they will not enter the other subzone, or will be removed by the opposite phase of swash that follows immediately afterwards. If the wave field is both uniform and oblique, material will be moved alongshore while remaining within the same subzone.

The fact that swash processes do not simply move particles alongshore at a rate proportional to their size is perfectly exemplified by the results of three independent tracer experiments made on beaches dominated by swash. One of these, by Gleason et al, (1975), produced the most logical result, that

"maximum longshore transport corresponded with smallest particle size."

At the other extreme, Caldwell (1983) found that

"maximum alongshore transport coincided with largest particle size,"

whereas Evans (1939) hit the middle ground, in concluding that

"it is the sediments of medium size that are transported most by beach drifting."

All three of these results are likely to be correct for the situations encountered, and have all been repeated in a number of other independent studies. The three authors quoted here each discussed their own results with regard to the same phenomenon: the size- and shape-sorting of materials normal to the shore. Particles are sorted into locations or subzones across the foreshore profile according to their size and shape characteristics. They are then moved alongshore at rates that depend largely on the potential of the hydraulic energy at that location to transport material alongshore. Hence, the dominant direct control on the rates at which particles are moved alongshore is their most commonly occurring locations on the beach, rather than their size or shape. For this reason, Caldwell (1983) believed it possible "that down-beach sorting by waves [and swash] ...is the primary process" determining the differential rates of longshore motion of particles sizes, which may merely be a secondary response to the process. Because the distributions of energy and materials across the foreshore are not the same on every type of beach, neither are the characteristics of the particles moved most rapidly alongshore.

It is quite probable that such a situation as described above, occurs on mixed sand and gravel foreshores, even more so than on pure sand or gravel beaches. The strong subzonation of this beach type due to shore-normal sorting produces very different conditions of sediment transport across the foreshore. The materials themselves are graded semi-permanently into specific subzones, and the hydraulic forces acting within each subzone are also very distinctive. Given that these two factors are strongly subzonated, it appears reasonable to argue that longshore sediment transport on a mixed sand and gravel beach is also. Brief examinations of each subzone should reveal the most effective section of foreshore in the promotion of longshore sediment transport, and the grain size that experiences the most rapid displacement alongshore. The subzones will be discussed here in terms of the three factors that control the rate of longshore transport: the duration of transport in a swash cycle and over longer periods, the component velocity of movement alongshore, and the volume being moved.

The nearshore face remains under the permanent onshore influence of propagating and breaking waves, which produce high shear velocities and turbulent flow in directions inherited from the offshore wave environment. Backwash, which often appears to undercut the advancing waves, acts to move material in the offshore direction at a much lesser angle and at lower velocities. The particles occupying this subzone are of very low mobility and the depth of disturbance is likely to be only moderate. In addition, the bulk of the mobile material is probably

deposited rapidly on leaving the breaker zone because of the marked falls in shear velocity both onshore and offshore. Thus, although the flow velocities across the nearshore face are high, longshore transport is restricted by the low mobility of the particles and the short duration (length) of movement.

The swash flows across the foreshore face are long, frequent, bidirectional, and intermittently strong, with a longshore component equal to, or higher than, that of the incident waves. The constituent materials are generally the finest of those found in the active layer of the whole foreshore, and so are the most movable of the foreshore sediments. Consequently, the longshore movements of these particles are quite considerable, ceasing for only short periods as the swash moves from uprush to backwash, and vice versa. The movements are especially strong towards the base of this subzone, where particles are moved at higher velocities, and for longer durations, than further up the face.

The swash berm, or upper swash zone, is characterised by very low shear velocities that are seldom able to entrain or transport particles over significantly long distances. That the swash berm is a predominantly depositional morphology is evidenced by the convex configuration, lying above the level of the rest of the foreshore slope. Very little motion out of the zone occurs under constant energy inputs, but the protruding form makes the constituent materials very susceptible to redistribution and longshore motion under the disequilibrium of changing conditions. The coarse surface material, and the frequent

stranding of particles due to falling tides and swash lengths, provide further evidence to suggest that longshore transport in this subzone is of low significance.

The storm face presents vast contrasts in the importance of longshore transport over time. For long periods, it is unaffected by the incident wave energy. Only under storm conditions does the swash enter the zone and induce movements of sediment alongshore. The high energy levels experienced during storms mean that the active layer and the velocity of particle movement become greater than normal, and the range of particle sizes moved also increases. In addition, storms on the South Canterbury coast originate mainly from the south or south east, and the storm surfaces are activated only under these conditions. The movement of material along the storm face is therefore mostly towards the north.

It should be made clear however, that the material resting on the storm face during low energy conditions has not necessarily been moved alongshore solely within this subzone. Such an occurrence would in fact be unlikely, because a major effect of storms is to produce highly mobile conditions across the foreshore and to redistribute and mix the materials throughout all of the subzones into a sediment population that is less well sorted, and more homogeneous overall. Although difficult to verify, it is probable that storm conditions reduce the strength of the foreshore subzonation. They also play a major part in reintroducing 'stranded' material on the storm face and from beneath the bed surface into the active foreshore transport system.

Depending on the magnitude of a coastal storm, the storm berm or washover slope may become subjected to the flows of the upper storm swash. On these surfaces, percolation rates are high, so that longshore energy flows are not. On washover slopes, flows are only landward, and are directly influenced only by the forces of gravity, which do not act alongshore. The coarseness of the surface materials also reduces their mobility, so that sediment movements, particularly those parallel to the shore, are probably low.

It can be concluded from these subzonal descriptions of longshore motions, that overall sediment transport rates on mixed sand and gravel foreshores are greatest on the lower part of the foreshore face. Following from this, it is justifiable to state that the coarse sands and fine gravels that most commonly occupy this zone are moved at greater rates than the other sizes occurring on the foreshore surface. This is not due solely to the high movability of such particles, but also, and perhaps mainly, to their usual occurrence and dominance on the highly active foreshore face.

To provide definite quantitative evidence in support of such a statement would probably require the undertaking of a tracer experiment using the full range of foreshore particle shapes. This is made virtually impossible on a mixed sand and gravel beach by the extreme range of sizes. The standard sampling procedures for recovering sand tracer (by core-sampling) and gravel tracer (by scanning the bed surface) are not the same, and the results of the two are not directly comparable. Neither, therefore, are

the transport rates of sand and gravel able to be compared by these methods.

4.6 LONGSHORE TRANSLATIONS OF MORPHOLOGY

The morphology of a mixed sand and gravel beach system is known to be non-uniform in the longshore direction. Beach cusps are the best known of the total range of topographic features that may exist on such beaches. Although not always present on South Beach, they were observed there on occasions and are reported by Kirk (1980) to "occur very commonly in berm faces, three sets being commonly observed, their dimensions increasing with elevation on the foreshore." Collective movements of their constituent sediments can cause the migration of cusps alongshore, but this phenomenon has not yet been studied on a mixed sand and gravel coast.

Because of the known dependence of the foreshore slope on grain size and sorting (McLean and Kirk, 1969), longshore variations in beach morphology can occur at a larger scale due to similar changes in foreshore textures. Such variations were observed on a mixed sand and gravel beach system by McLean (1970) as a rhythmic pattern alongshore with cyclic spacings of 3 to 5 kilometres. Kirk (1980) notes that "it is not yet known how source area effects and hydraulic factors interact to produce the observed trends." In some cases, these populations of sediments in the active layer of the foreshore may migrate alongshore collectively as a 'sedimentation unit'. Certainly, they do not appear to disperse easily once formed, as the sediment at any given location on the

foreshore face is generally very well sorted, while often being very different between locations (McLean, 1970). The foreshore textures at South Beach were found to change frequently at single locations and right along the beach, but whether this was due to deliveries of new populations from alongshore could not be ascertained. If collective longshore movements of textural populations do occur, they could have major implications for coastal management, since they would produce predictable changes in the beach morphology over time.

A third potential source of irregular beach morphologies along the South Canterbury coast is the episodic supply of sediment from large rivers during floods, and from eroding seacliffs. It is possible that the materials comprising these bulk or "slug" inputs are moved alongshore at consistent rates, so that 'excess' volumes of the beach are maintained over a quasi-constant length of beach as they move alongshore. Alternatively, migrating form may be maintained by other mechanisms independent of the rate of material drift. Migrating beach forms have been observed on sand beaches under a variety of names, such as pulses (Handin and Ludwick, 1950), sand waves (Bruun, 1954), and giant cusps (Komar, 1971), their modes of formation being probably even more diverse than the names given them. An examination of air photos of the South Canterbury coast by Gibb and Adams (1982) showed that such forms are not apparent in the study area at the scale of air photos (about 1:10,000) and that pulsed inputs of sediment appear to be "rapidly dispersed alongshore by wave action." The possible

occurrence and movements of migrating morphologies on mixed sand and gravel beaches will be examined in more detail in Chapter 6.

4.7 CONCLUDING REMARKS

The motions of water and sediment along a mixed sand and gravel foreshore have been shown in this chapter to be complex and varied. The phenomena are quite unlike those observed on other types of beach, and on sand beaches in particular. An initial approach to the problems of investigating this new situation has been borrowed from a wide range of the sand beach literature: the LEO program, the dye speed prediction equations, and the tracer plug method for measuring the active layer have each been adapted and applied with varying degrees of success. Each method has nevertheless, shed new light on the processes operating on the study site beaches. Because of the basic similarities of mixed sand and gravel beaches throughout New Zealand, the results should, to some extent at least, apply to those throughout and outside of the South Canterbury study area. A major deficiency of the dye tracing method was found to be an apparent lack of representation of swash flow, by the retention of the observed dye patch in the breaker zone. It was concluded from the results that dye speeds alongshore only represent the concentrated (non-dispersive) water flows near the breakers. In contrast, it was also shown that the dispersive swash flows produce the greatest amount of sediment motion alongshore. Therefore, longshore motions of sediments and dye in the water are probably mostly

related only indirectly, through the characteristics of the incident wave field.

Nevertheless, the patterns and rates of water motion were shown to be a primary influence on the longshore movements of sediment. The second governing factor is the movability of the particles. Both of these elements interact with each other, as well as with other factors, thereby complicating the patterns and processes of motion. This has been highlighted by previous studies showing that the rates of movement alongshore are not simply a function of particle size, but are also affected by the distribution of energy and sediments across the foreshore. An attempt to overcome this complication was made by examining the different ways that processes act and interact in the five subsystems of the foreshore profile. It was found from this that the lower swash zone produces the greatest amount of longshore motion, owing to its consistently high shear velocities through time and space, and to highly movable materials. It is therefore this zone that has the greatest influence on the overall rate of longshore transport on a mixed sand and gravel foreshore.

CHAPTER 5

RATES OF LONGSHORE SEDIMENT TRANSPORT

5.1 INTRODUCTION

It is widely agreed that the South Canterbury foreshore environment is strongly dominated in the long term by a net northward drift of material. Evidence for this assertion is abundant, and numerous publications have emphasised the importance of the phenomenon to the dynamics of the coast. Less strongly agreed upon, is the rate at which the beach material is moved in this direction. Several attempts have been made by earlier authors to evaluate this quantity, and their results have produced a range of possible magnitudes. Notably, all of these have been given as 'long-term' rates of drift, with no attempt being made to evaluate the variability of drift rates over time. Such shorter-term changes probably occur from a number of causes, and may have significance to the dynamics of the coast in many respects.

Furthermore, most of the more accurate estimates have been made at only one location (South Beach), using basically the same method of estimation. Other locations and methods have not been well used or assessed in the past. It was maintained in Chapter 1 that use of a diverse range of methods was a necessity for this field of coastal studies. Clearly this is presently lacking in South Canterbury.

This chapter will first examine the evidence for net northward drift, and then review previous attempts to quantify it. Following this, further estimates for the rate of longshore transport will be made by applying new and previously used procedures to the South Canterbury mixed sand and gravel beach system. Emphasis here will be placed on the variability of the drift rate around a longer-term trend, and on finding a method that can be used for any location along the coast. By this means, it is hoped to provide a clearer view of the approximate magnitudes and variability of sediment flows along the foreshore.

5.2 THE EVIDENCE FOR NORTHWARD DRIFT

Manifestations of longshore transport occur in the energetic, sedimentologic and geometric elements of the coastal process-response system. These elements exhibit asymmetries along the South Canterbury coast that are thought to both cause and result from the mass transport of material along the foreshore. They all lend strength to the supposition that the net long-term drift of foreshore sediment is toward the north.

The directions of energy flows along the coast are the primary controls on the direction of net drift. Refraction diagrams have been constructed for the study area both south and north of Timaru by Hewson (1977) and by Hastie (1983), and are reproduced in Figures 5.1 and 5.2. These diagrams show the effects of refraction on deepwater waves shoaling from several directions across the continental shelf. The directions of propagation

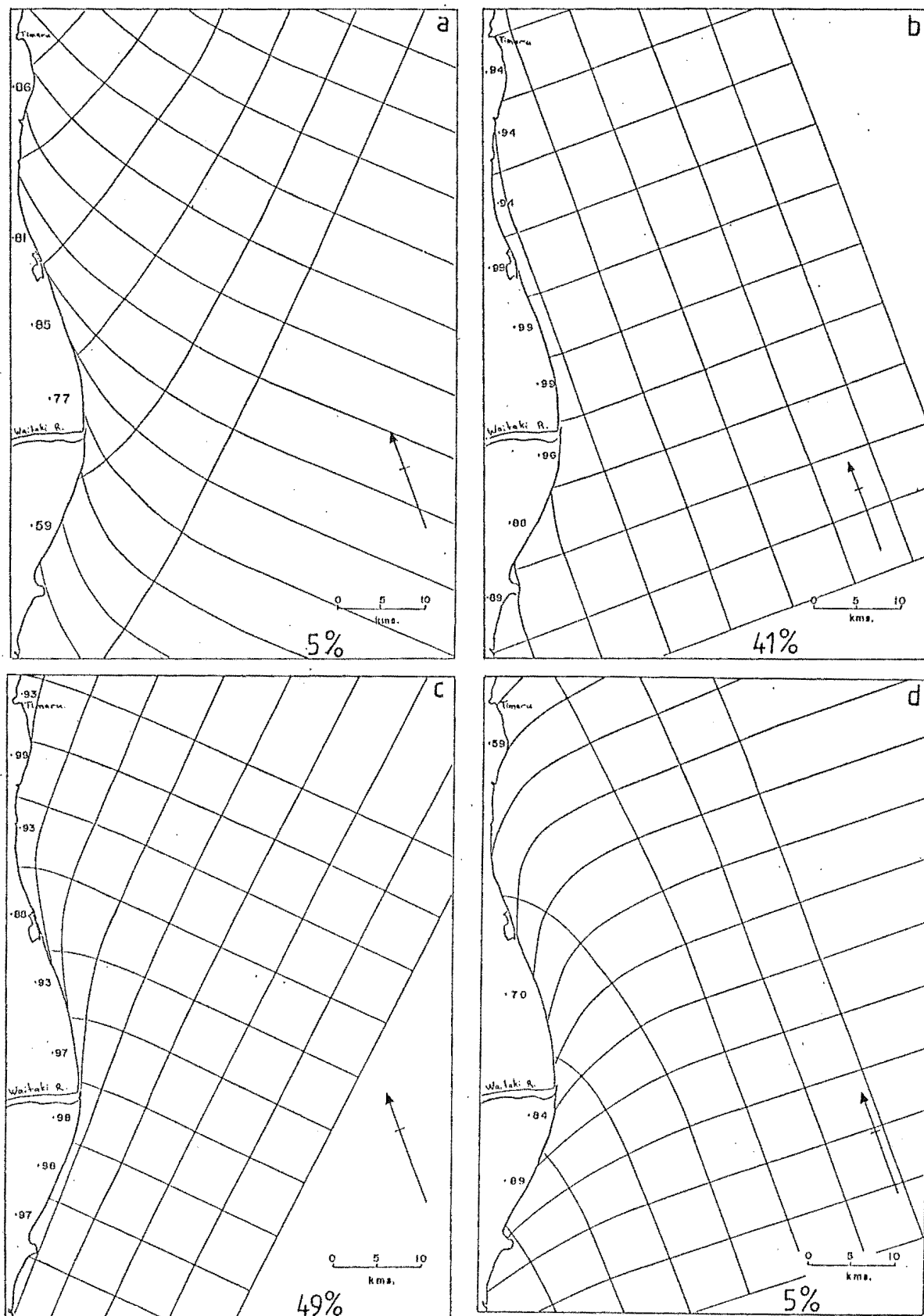


Figure 5.1 Refraction diagrams for the South Canterbury coast south of Timaru, with percentage occurrence of each wave direction, for waves from the

- (a) Northeast
- (b) East
- (c) Southeast
- (d) South

(Source: Hewson, 1977)

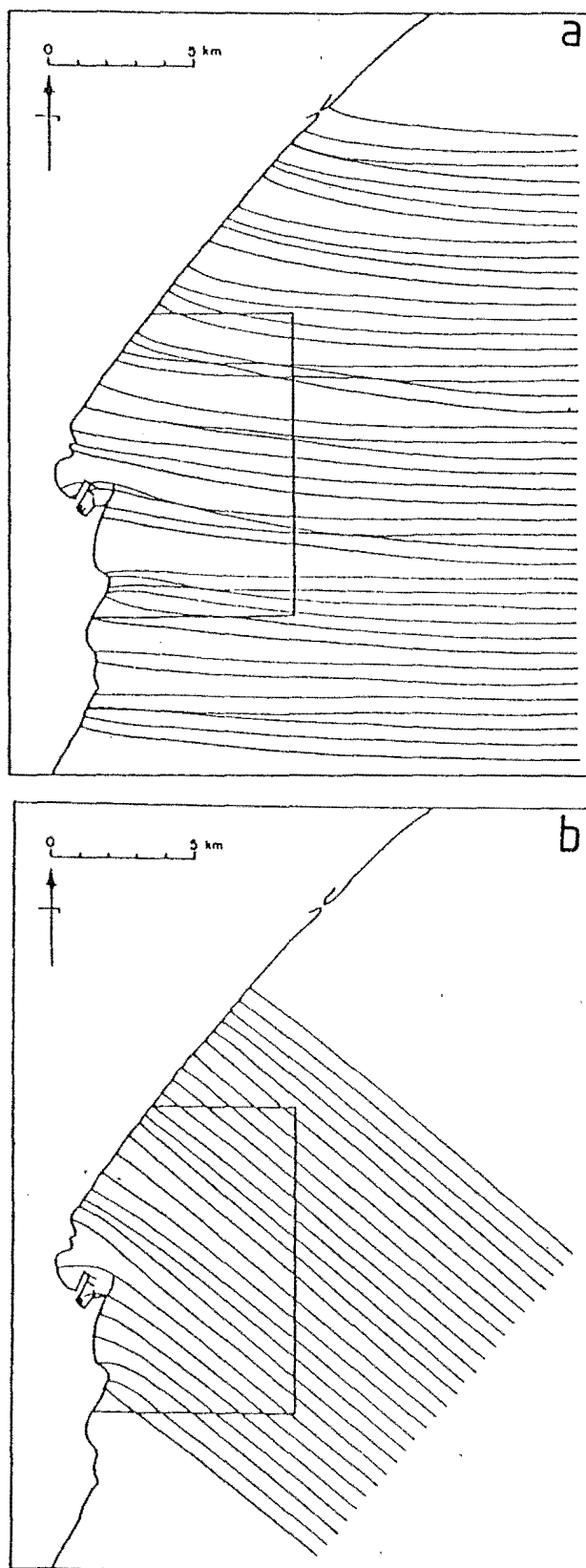


Figure 5.2 Refraction diagrams for the coast around Timaru, for waves from the (a) East
(b) Southeast
(Source: Hastie, 1983)

are shown in all of the diagrams by wave orthogonals, which are lines drawn perpendicular to the wave crests in Figure 5.1. The amount of wave energy reaching a unit length of beach is dependent on the degree of convergence or divergence of these orthogonals, since it is assumed that the deepwater wave energy along a length of wave crest between a pair of orthogonals remains constant. The degree of dispersal of the wave energy along the shore due to refraction is expressed by the values of the refraction coefficient (K_b), as shown in Figure 5.1 for the lengths of coast between each pair of orthogonals. These are given by the formula

$$K_b = \sqrt[3]{S_0/S_b} \quad \dots 5.1$$

where S_0 = spacing between orthogonals in deep water

and S_b = spacing between orthogonals at the breakpoint

(Johnson et al, 1948; in
Hewson, 1977)

Greater reductions in the wave energy per length of beach are indicated by lower K_b values.

It can be seen from the refraction diagrams that the oblique southerly and northeasterly waves disperse their energies over a greater length of coast than do the easterly waves, which are refracted only slightly yet arrive almost at right angles to the shore along most of the study area.

The refraction diagrams also show that the long-shore component of wave energy can be directed either way, depending on the direction of the swell source from the coast. The direction of drift is therefore also variable,

but is greater in the direction of the prevailing (most frequent) and dominant (most powerful) ocean waves. Accompanying the refraction diagrams are the percentage frequencies of occurrence of each wave direction, based on offshore data obtained by the Timaru Harbour Board in 1967-1969. This is the longest single wave record available for the South Canterbury coast and is assumed here to accurately represent the long-term wave climate. It can be seen from the percentages shown that waves prevail from the southeast quadrant, and it is known that the dominant waves are also from this direction (Tierney, 1977). They are derived from a persistent belt of wind-generating weather systems to the south of New Zealand that is not matched in the north. Waves from the northeast quadrant are less common and are usually less powerful than waves from the southeast. The height of northeasterly waves at the foreshore is restricted by the weaker wind systems and by the greater width of the shallow continental shelf that they propagate across. The consequent asymmetry of the wave climate is strong, suggesting that a definite northward drift trend is present. It is important to note, however, that the angles of wave approach and convergence of the orthogonals are not uniform along the coast, but vary mainly in accordance with the orientation of the shoreline towards the wave field. Because movements of sediment along the coast are significantly dependent on the angles and convergence of energy flows, the rates and directions of drift also vary in time and space.

Sedimentologic indicators of the direction of net drift along the South Canterbury coast were examined by

Hewson (1977; 78). In that study, longshore variations in grain size and sorting of foreshore sediment samples away from known sediment sources were analysed. Two main sources were identified; the Waitaki River and the cliffed eroded edge of its fans. Expected decreases in grain size and sorting coefficients away from the Waitaki River were not clear, and inconclusive results were produced for inferring transport directions. The lack of clear trends was attributed to the "noise" caused by the presence of a major sediment input extending along the coast, from cliffs. Furthermore, an unfortunate problem occurs in trying to infer the direction of transport along a mixed sediment beach from granulometric data. This is that the sorting of the source material across the beach confuses the patterns of grading alongshore to such an extreme degree that they become almost indiscernible.

The geometry of the coastline is affected by the interaction of the longshore drift of material with coastal features that impede its progress. Such interactions are evident at two locations within the study area, both of which indicate that the net movement is to the north. The first is at the mouth of the Waitaki River, the relevant parts of which are shown in Plate 5.1. Here, analyses by Young and Jowett (1982) from aerial photographs spanning 39 years have demonstrated that the position of the river outlet is variable, but that it is almost always offset towards the north of the river centreline. The formation of this asymmetry is controlled by the interactions of the flows and sediment transport of the river and coast. The supply of beach material at

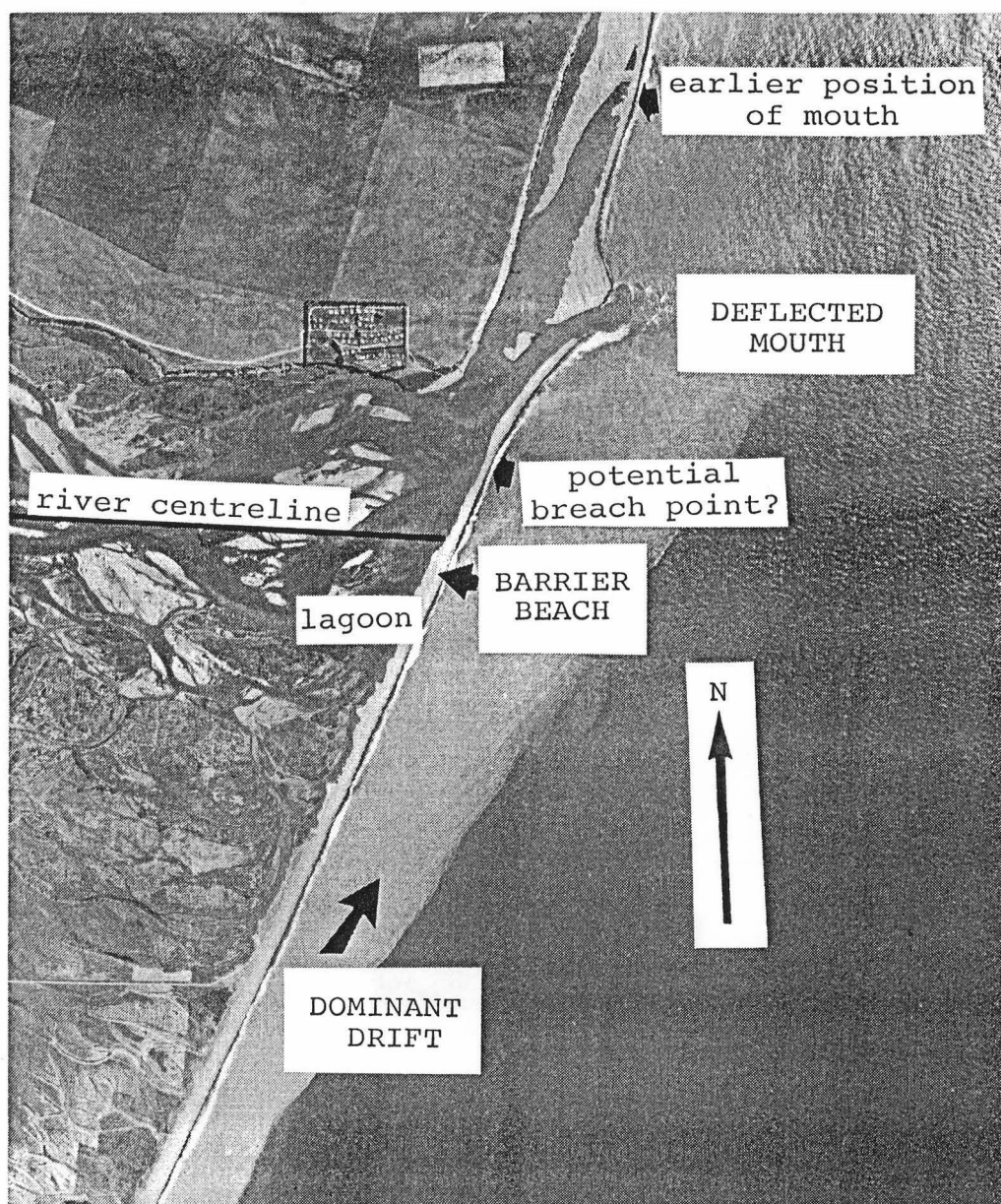


Plate 5.1 Longshore drift effects at the Waitaki River mouth.
 (Air photo: Dept. Lands and Survey, 1963;
 SN1513-3483/48)
 Altitude: 12,500 ft.

the river mouth by mass transport alongshore interferes with the direct outflow of the river. The excess supply of material on the southern (updrift) side of the mouth forces a deflection of the river flow along the coast to the north, in the direction of longshore drift. A barrier beach is formed that prevents direct outflows until the hydraulic gradient across it (due to raised water levels in the lagoon), causes a breaching of the barrier at a low point nearer to the river centreline. The mouths of other rivers at the coast are not so strongly offset, because their low outflows have less control over the progression of material alongshore, so they are periodically closed, rather than merely deflected by the barrier beach.

The second important geometric asymmetry of the South Canterbury coast is in the shoreline changes around the port of Timaru. The significance of the net northward drift along the Timaru and South Canterbury foreshore was realised at a very early date. Based on earlier observations of a concrete jetty that was overwhelmed by beach shingle, Sir John Coode, a marine engineer, was quoted (in Clarke, 1921) as saying in 1875 that;

"Any [harbour construction] works to be successful must not interfere with the northerly travel of the shingle."

Despite this warning, the construction of permanent shore-connected breakwaters began in 1878 and this has effectively disrupted the continuous mixed sand and gravel foreshore that previously existed. The transmission of coarse material from the beaches to the south to those north of the port has been arrested and the port thereby acts as a 'littoral barrier' to the longshore transport system.

The effects that this has had on the shore geometry are pictured in Figure 5.3, and can be compared to the effects of a littoral barrier as was shown in Figure 2.5. South of the port, on what must consequently be the updrift side, the material delivered by longshore transport from further south has accumulated against the Eastern Extension Mole. This coarse material is not easily transported in the depths of water that occur towards the end of the mole (about 7-9 metres), and so it is prevented from continuing northwards. This in turn, has meant that the section of beach to the north has been starved of a sediment supply from the south. The overall effects of the port constructions on the sediment budgets of the adjoining foreshores have therefore resulted in considerable progradation at South Beach, and an equivalent net volume of sediment removal from the Washdyke barrier beach. Northeasterly waves can temporarily reverse the direction of longshore transport, but the scale and duration over which such counterdrifts usually occur is insufficient to produce obvious morphological changes. Because the representation of longshore drift by these changes is cumulative over many years, the changing appearance of the shoreline around Timaru is perhaps the clearest indicator of the northward direction of net drift.

5.3 PAST ESTIMATES OF DRIFT RATES

Widespread erosion of the South Canterbury coastline and the local accretion at South Beach are matters of prime concern to the managers of the coast and the adjoining hinterland. These shoreline changes result

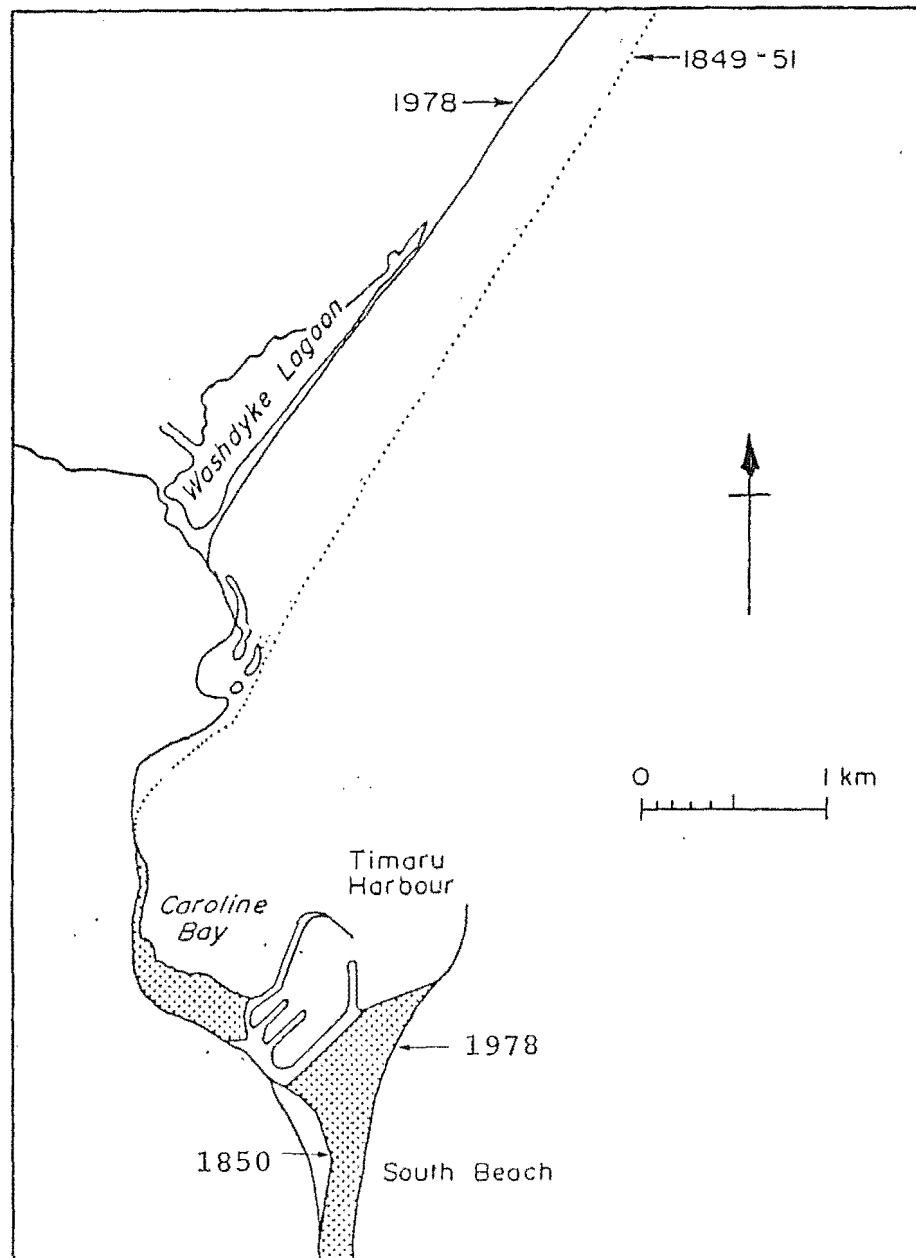


Figure 5.3 Shoreline changes near the Port of Timaru. Note the accumulation of sand and gravel updrift at South Beach and the accelerated erosion downdrift at Washdyke.
(after Kirk, 1983; in Hastie, 1983)

from the removal or addition of material to the foreshore sediment budget which is controlled to a large degree by the transfers of sediment alongshore. To gain some idea of the likely magnitudes of future shoreline changes, it has therefore been found desirable to obtain estimates of the net rate of longshore sediment transport on this section of coast. Several previous studies have attempted to do so, and these will be reviewed here. The methods and estimated values of each are summarised in Table 5.1.

Hewson (1977) estimated the rate of longshore sediment transport at four points along the coast between Timaru and the Waitaki River mouth. The method that he used was a derivation of the Energy Flux Method described in Chapter 2, for use with deepwater wave data and refraction analysis. From this, he found that the transport rates were highly variable under different wave directions and at different locations. The net estimate obtained at South Beach using this method is 10 to 15 times greater than the other estimates shown in Table 5.1 for the same location. There are two main reasons to suggest that Hewson's values overestimate the true rates. Firstly, it has already been noted that the Energy Flux Method gives an approximation of the potential rate of transport by waves, and does not take the additional controlling factors, such as sediment availability, into account. That almost all of the South Canterbury coast is undergoing severe erosion suggests that the longshore transport system is somewhat undersaturated, and that the estimates are therefore excessive. Secondly, the dimensionless constant that was used in the equation relating the

Table 5.1 Past estimates of net longshore sediment transport rates on the South Canterbury coastal foreshore

Method	Author	Location	Rate estimate ($\text{m}^3 \cdot \text{yr}^{-1}$ northward)
Energy flux and refraction	Hewson (1977)	South Beach	940,000
		Pareora	-941,535
			(southward)
		Waitaki R.	1,476,292
Littoral barrier - accumulation updrift	Anon (1895, in Clarke 1921)	South Beach	76,455
	McIntyre (1958)		88,750
	Tierney (1969)		60,730
	Tierney (1977)		60,340
	Kirk (1984)		56,981
	Tierney and Kirk (1978)	Washdyke	81,500
- erosion downdrift			

longshore component of wave power to the sediment transport rate (i.e. $k = 1290$, where $Q(\text{m}^3.\text{yr}^{-1}) = k P_{\ell S} (\text{N.s}^{-1})$; converted from imperial units in Hewson, 1977) was determined from experiments done on sand beaches. The equation does not account for variations in internal factors such as sediment size, surface gradient and porosity of the foreshore. Considering the vast physical differences between the sediment transport systems of sandy and mixed beaches, it is unlikely that this 'constant' is the same for both types. The lower transportability of the mixed beach material suggests that the value is possibly, though not necessarily, overestimated.

The littoral barrier effects of the port construction at Timaru have been the basis of all other estimates of the sediment transport rates within the study area. One of the first attempts to quantify the rate of sediment accumulation updrift of the breakwater was made in 1895, from areal surveys that produced an average annual rate estimate of about $76,455 \text{ m}^3$ (Clarke, 1921). McIntyre (1958) gave an overall volume of accretion at South Beach that works out over the 80-year period at an average rate of $88,750 \text{ m}^3.\text{yr}^{-1}$. This value was for the total volume increase beneath the natural reclamation, and so probably included some material deposited by the nearshore transport system seaward of the breakers.

The South Beach shoreline has been artificially maintained at a quasi-equilibrium since the 1950's, when commercial gravel extraction commenced near the breakwater end of the beach. This has effectively reduced the rate of beach volume increase, and estimates of the total

accumulation after this date have needed to take it into account. Tierney (1969) made an estimate of $60,730 \text{ m}^3 \cdot \text{yr}^{-1}$, which he later revised and reduced to $60,340 \text{ m}^3 \cdot \text{yr}^{-1}$ on the basis of more recent data (Tierney, 1977). The most recent evaluation was made by Kirk (1984), who gave a value of $56,981 \text{ m}^3 \cdot \text{yr}^{-1}$ for the net transport into South Beach over the preceding 104 years.

It can be argued that the Eastern Extension Mole at Timaru Harbour is almost a total littoral barrier for the entrapment of foreshore sediments. If this is so, then the volume of the accumulation at South Beach can be used for measuring the minimum rate of longshore sediment transport in the foreshore zone. Such an ideal state occurs when material can be moved in to and out of the adjacent beach only through the end opposite the barrier. If all other sediment transfers are prevented, then the net changes in the foreshore volume represent the net movements alongshore through the open end of the beach, so that accurate estimates of these movements can be made.

Sediment transfers into South Beach are almost entirely from the foreshore to the south. The material comprising the reclaimed land is mostly coarse and so does not originate from the fine offshore deposits of the continental shelf. Furthermore, inputs alongshore from the north are made impossible by the combined effects of the littoral barrier, the great distance to the nearest source of coarse material (2 km away at Washdyke), and the water depths of up to 9 m that separate them. However, losses of sediment from South Beach are less definite.

It is known that foreshore material can be moved past the end of the breakwater by large storm waves (Tierney, 1977) and so it is not a complete barrier to the northward drift. In addition, offshore losses of beach material are very likely to occur through abrasion to finer particle sizes, and the magnitude of such losses are unknown, but were noted earlier to be probably significant. From this information, it appears that the measured rates of accumulation at South Beach represent only a lower limit of the true rate of longshore sediment transport, since the losses through boundaries other than the southern end are likely to be significantly greater than the additions.

The only other estimate of the longshore transport rate to have been made in the study area involved estimating the rate of erosion of the beach gravels from the southern 5 km of the barrier beach at Washdyke. This beach lacks a sediment supply from the dominant northward drift direction due to the littoral barrier of the harbour, and so it has been eroding at an accelerated rate since the late 19th Century. Longshore transfers of sediment occur mostly through the northern boundary of this section of beach as a result of the littoral barrier to the south. On the basis of the erosion caused by this single-ended sediment budget system, Tierney and Kirk (1978) estimated that $81,500 \text{ m}^3 \cdot \text{yr}^{-1}$ of foreshore materials are drifted northward out of this stretch of beach.

These previous estimates give a wide range of values for the rates of longshore sediment transport on the South Canterbury mixed beach foreshores. The variability, which attains a level of more than an order of magnitude, can be partly explained by actual differences in the rates

that occur through time and space. Uneven geometries of the sea bed and the shoreline produce different magnitudes and directions of energy flow at the breakpoints along the coast. Consequently, the potential of the waves to cause longshore movements of sediment also varies alongshore. This is shown in the results of Hewson (1977), which were obtained using the same method and the same deepwater wave data to give very different values at each location. Variations in the longshore transport rate over time are also likely to occur, as a result of changes in the short-term wave environment and in sediment availability at the coast. The effects of temporal changes such as these on the longshore transport system of the South Canterbury coast have not yet been assessed.

Little of the variability in the results can be reasonably explained by actually-occurring differences. The great disparity between the 'Energy Flux' and 'Littoral Barrier' results for the same location at South Beach, although admittedly obtained from different time periods, strongly suggests that one or both methods do not give an accurate evaluation of the 'true' rate of longshore transport. It has been suggested here that the two methods provide upper and lower limit estimates, respectively. The actual rate of northward drift at South Beach is expected to lie somewhere between 60,000 and 940,000 $\text{m}^3 \cdot \text{yr}^{-1}$. Elsewhere along the coast, the rates are likely to be of a similar range of orders.

Even the estimation of longshore transport rates using the same basic approach at the same location has produced disparate results. The estimates for the annual rate of

accumulation at South Beach have varied by up to $\pm 25\%$ from their mean value. The disagreement may be partly due to a variable rate of accumulation over time, but it is no doubt also caused by errors of volume measurement.

5.4 TEMPORAL VARIABILITY OF DRIFT RATES

The volume rate of sediment transport along a given stretch of foreshore is not constant over time, but it varies in accordance with changes to the energetic, sedimentologic and geometric characteristics of the process-response system in which the movements take place. By measuring the volume of sand and gravel that has accumulated at South Beach since the construction of the Eastern Extension Mole in 1878, most authors have provided only mean rates of longshore transport over long-term periods of several decades. The assumption of a constant rate over time is implicit in this approach and few attempts have been made to discern possible non-linearities. The objective of this section is to firstly determine the long-term trend of accumulation and longshore transport at South Beach, and then to examine the annual and sub-annual variabilities within this trend.

5.4.1 Long-term trends

The only assessments of long-term coastal changes at South Beach that have used more than two data points have been from charts and were made by Clarke (1921, 1936) and by Kirk (1984). Kirk (1984) measured the progradation (horizontal advance) of the shoreline near the mole, and found that "the overall growth trend has been

curvilinear [a fall in the rate of increase] since 1879, and remarkably linear since 1909 when the re-entrant against the original breakwater was first infilled".

It is emphasised here that this statement refers to only one dimension of the volumetric response to alongshore sediment transfers, and might not represent the total volume changes if the progradation has been inconstant alongshore. Nevertheless, it suggests that the rate of shoreline change, and so perhaps the rate of longshore transport, has not been constant over the past century.

A more reliable estimate of the long-term trend can be gained by measuring the changes at South Beach in two dimensions (areal plan). With this objective, historical records (two charts and three aerial photographs) of South Beach between 1878 and 1980 were analysed. These were scaled and the shoreline positions (high water at ordinary spring tide, or HWOST) were plotted onto base maps by triangulation and relative distance measurements from identifiable features inland. A record of the increasing plan area of the accumulation over the 102-year period was thereby obtained. The two maps thus produced are shown in Figures 5.4 and 5.5. Additional shoreline positions for the period 1906 to 1920 were also available from a plan by Clarke (1921), reproduced in Figure 5.6. In all the shorelines of 16 different years were used for analysis. Ten of these could be traced only as far south as North Street, approximately 1.3 km from the present northern end of the beach.

The errors associated with the points plotted from the air photo shorelines (1938, 1954, 1980) are thought to be minimal. The main problem of image distortion away

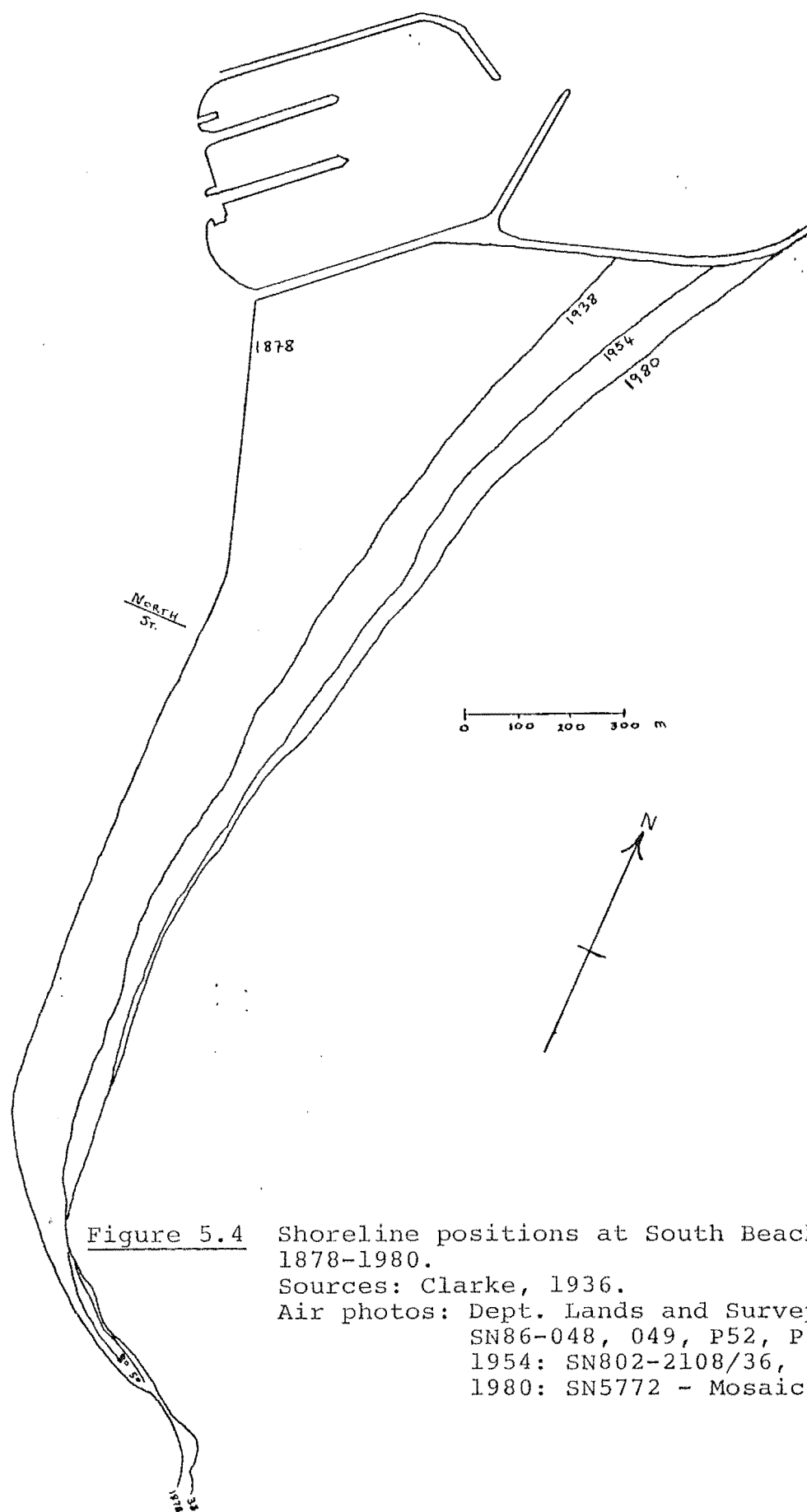


Figure 5.4 Shoreline positions at South Beach, Timaru 1878-1980.
 Sources: Clarke, 1936.
 Air photos: Dept. Lands and Survey, 1938;
 SN86-048, 049, P52, P53.
 1954: SN802-2108/36, 37
 1980: SN5772 - Mosaics 2.4, 2.

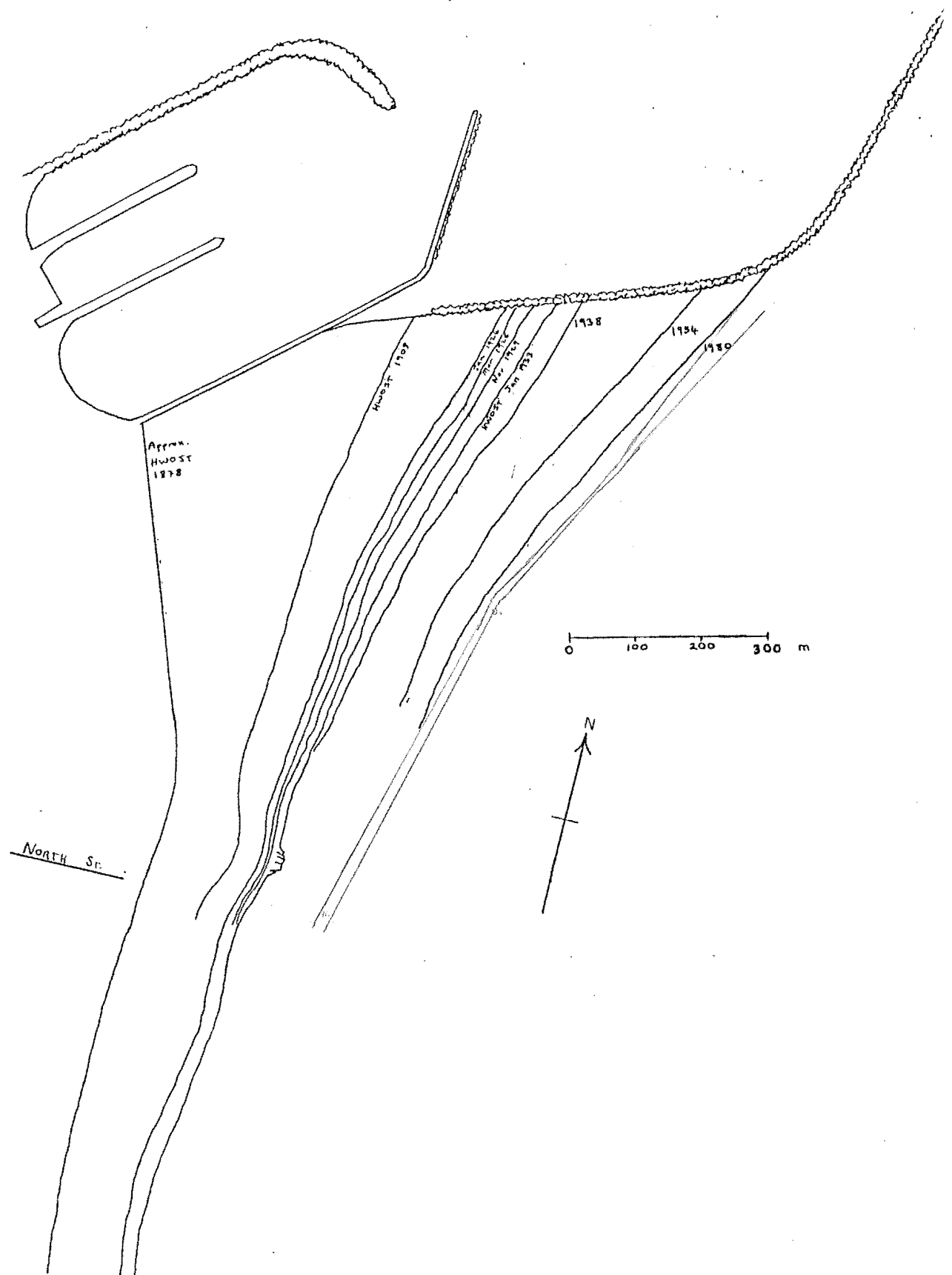


Figure 5.5 Shoreline changes at South Beach, north of North Street, Timaru; 1878-1980.
 Sources: Clarke, 1936.
 Air Photos: Dept. Lands and Survey,
 1938; SN86-048, 049, P52, P53
 1954; SN803-2108/36,37
 1980; SN5772 - Mosaics 2.4, 2.5

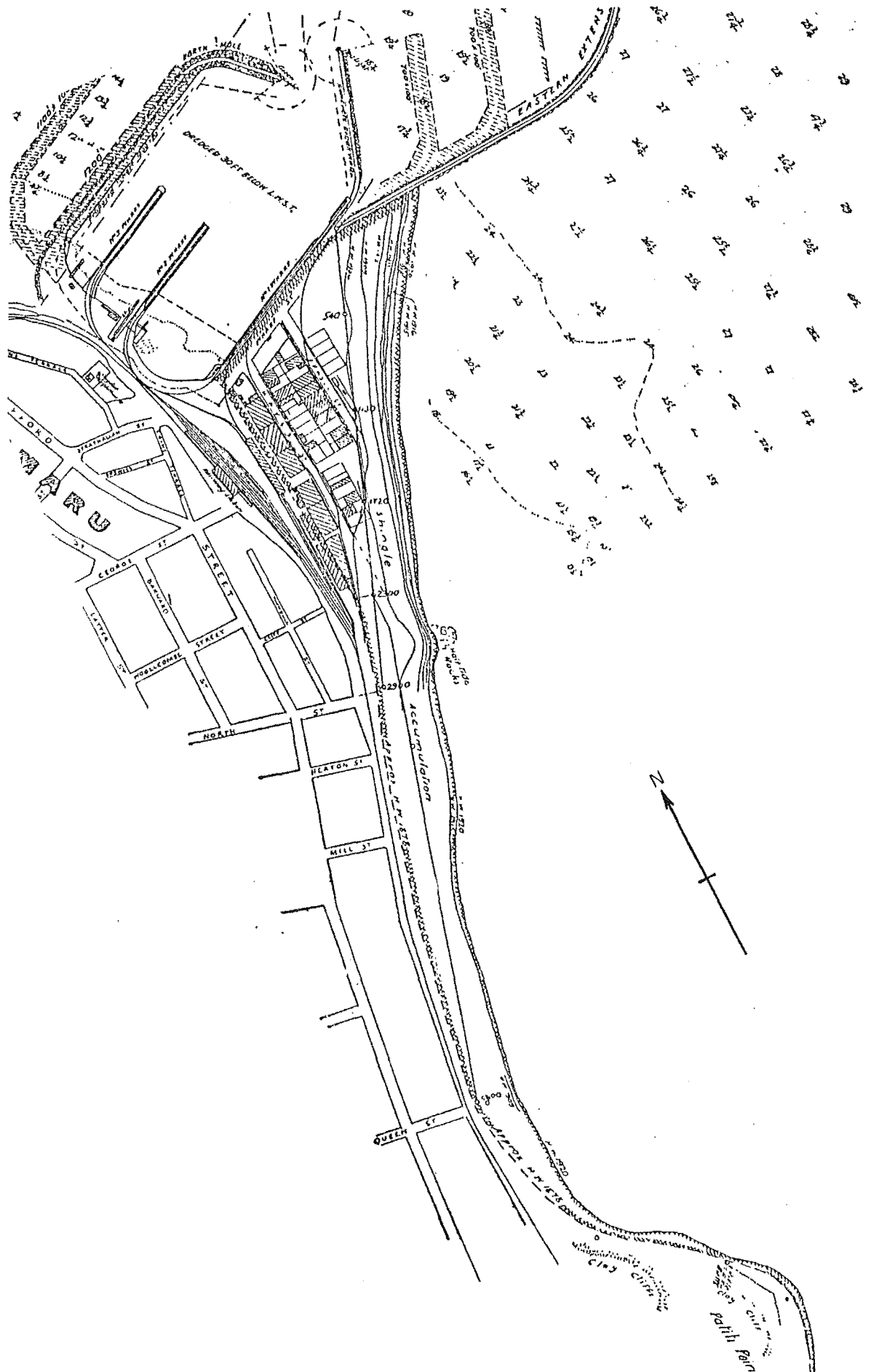


Figure 5.6 Shoreline positions at South Beach, Timaru; 1878-1920 (Source: Clarke, 1921). Scale=1:11258

from the centre of the photo was tested by cross-checking from several reference points and from adjacent photo pairs. The range of error in shoreline position caused by this was found to be about ± 5 m. A second problem was the identification of the HWOSt line. The line of the groundwater table along the foreshore face was chosen as the most suitable reference partly because of its clarity, but mainly because it is known that the groundwater emerges at the surface approximately at the stillwater level. The horizontal translational of this line normal to the shore due to short term profile changes and tidal effects is minimised by the steepness of the beach face, but may amount to 10 m on occasions. These two main sources of error may appear considerable, but are not highly significant in relation to the average overall progradation covered by the air photos (150 m in 42 years).

The total plan area of accumulated sand and gravel was measured for each year and plotted using a digitiser. The areas for the shoreline that had no records south of North Street were extrapolated on the assumption that the progradation in this area was proportional to the rate along the axis of North Street. Less than a third of the total accumulation has occurred in this area. Volumes of material derived from foreshore drift into South Beach were then calculated by multiplying the areas by the average depth range of the deposit. The upper limit of the foreshore surface is the horizontal storm berm, which was found from surveys at South Beach to be an average of + 5.3 m above mean sea level. The depth below sea level to which the deposit extends is less certain, but it was

found by Tierney (1977) that the boundary between foreshore coarse material and nearshore fines occurs at South Beach not far below the low water mark (- 1 m below mean sea level). It is assumed here that this total depth range of 6.3 m has remained constant for the whole beach over the past 100 years at least.

The increasing volume of foreshore material at South Beach is shown by the graph in Figure 5.7. In close agreement with the progradation measured by Kirk (1984), it can be seen that the volume has increased at an almost constant rate, particularly between 1909 and 1954. There are two deviations from the otherwise statistically perfect linear increase and these are readily explainable. Before the construction of the Eastern Extension Mole in 1900, the original breakwater (now the No.1 wharf) was 600 m long, with only the basal 380 m aligned to effectively trap the northward drift of material. Clarke (1921; 54) reported that "the shingle had reached the bend" by about 1897, and often had to be dredged from the harbour entrance. The breakwater was therefore not acting as a total littoral barrier to the northward drift, and the slow rate of accumulation up to 1906 reflects this.

Probably the most important cause of the reduced volume increase between 1954 and 1980 is the commercial extraction of sand and gravel from the beach, which amounted to $760,000 \text{ m}^3$. However, a similar situation to that described above has also arisen over the past three decades, during which time the beach has prograded towards the bend in the Eastern Extension Mole. At this point, the breakwater extends obliquely along almost the

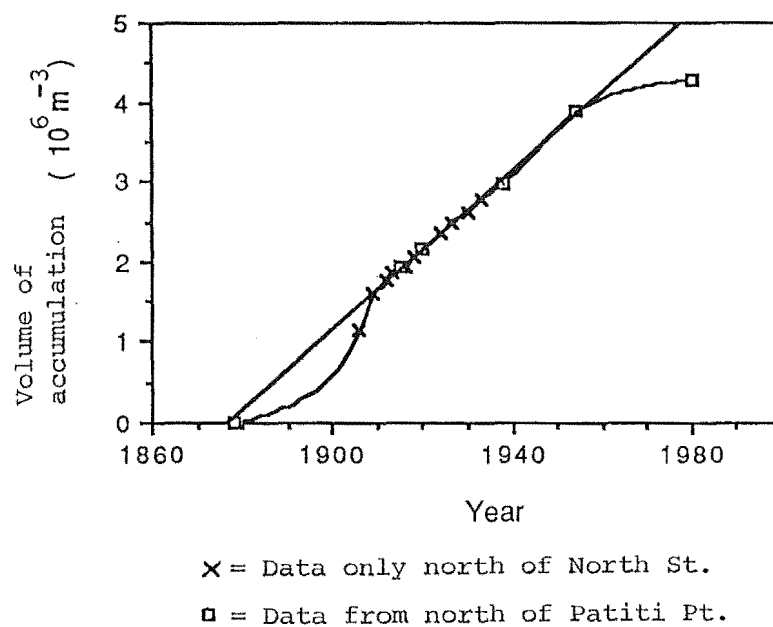


Figure 5.7 Volume of foreshore accumulation at South Beach, Timaru; 1878-1980.

same line as the foreshore breaker zone to the south, and so is less effective as a littoral barrier. Foreshore material has therefore been much more readily transported northward past the barrier, especially during storms. It is reported by Kirk (1984) for instance, that "some 26,000 m³ of coarse sediment were transported along the breakwater...in a single storm in 1983." Again, the volume rate of accumulation was thereby reduced from some time after 1954, and this is clearly shown by the 1980 volume in Figure 5.7. It is of interest to note that the effective length of the littoral barrier was increased in mid-1987 by the construction of a spur groin near the end of the breakwater. This structure was observed to immediately restrict the northward progression of coarse material by southerly waves. The progradation therefore appears to have been limited largely by the inefficiency of the barrier.

Apart from these two time periods (1878-1906, and 1954-1980), all volume changes at South Beach over the period mapped occurred under near-perfect littoral barrier conditions, with offshore losses by attrition being the only significant output. They can therefore be taken as very close minimum estimates for the rate of longshore sediment transport through the southern end of the beach at Patiti Point. It is this middle period that shows the strong linear trend of accumulation, so it is asserted that the longshore transport rate is also constant in the long term. The rate given by the regression line for 1906-1954 in Figure 5.7 is 51,288 m³.yr⁻¹. This is 10-40% lower than the rates

quoted from other authors in Table 5.1, and the reason for this is most likely to be the depth below sea level to which the calculations were made in each case. For every one metre increase in the presumed foreshore depth, the estimated rate of transport by foreshore processes rises by over $8000 \text{ m}^3 \cdot \text{yr}^{-1}$.

It is worth emphasising that because of the less perfect littoral barrier conditions occurring in the earlier and more recent years, the most accurate estimate of the long-term transport rate was gained from measurements of the accumulation between about 1906 and 1954. Notably, all of the previous estimates for the rate of accumulation were made for periods beginning in 1878 and ending outside this middle interval. The deviations from the trend have consequently not been recognised, apart from gravel extraction figures included in the estimates by Tierney (1969, 1977) and Kirk (1984). It can be seen from Figure 5.7 that this source of error for estimating transport rates should have produced values lower than the one given by this study. In fact, the past estimates have been higher, so that the non-recognition of the early and recent deviations from the trend are clearly not the dominant source of error. Nevertheless, it is contended that the simple two-point analyses made in the past may not have accurately identified the gross deviations from the overall trend. This fault was eliminated in the present study by analysing the historical record from many years.

5.4.2 Annual variations

Though the 100-year linear trend is statistically very strong, a high degree of variability is likely to occur at shorter time scales. Annual variations in the rate of sediment supply from alongshore might occur due to random and/or cyclical variations in the frequency of storms and the availability of materials. It has been widely recognised for instance, that a very stormy period lasting over several years in the late 1970's has contrasted greatly with the mid-1980's, during which there have been very few major coastal storms. Sediment transport rates in these two periods are likely to have been equally dissimilar. The only useful data available for analysing the variability of longshore transport rates at about this time scale are the South Beach shoreline positions shown in Figures 5.5 and 5.6 for the periods between 1906 and 1938. Although they show changes over more than one year, the average yearly rate of accumulation in each period can give a good indication of the annual variability around the long-term mean. This information is presented in Figure 5.8.

It can be seen that the rate of accumulation varies quite considerably from year to year. Neither a statistical summary of the variability of annual rates, nor a verification of the specific causes is possible from these data because of their derivation from non-annual measurements, but several aspects should be noted. Assuming that the variability is an indication of changeable rates of longshore drift into South Beach and not, for example, losses from it, the extreme and average

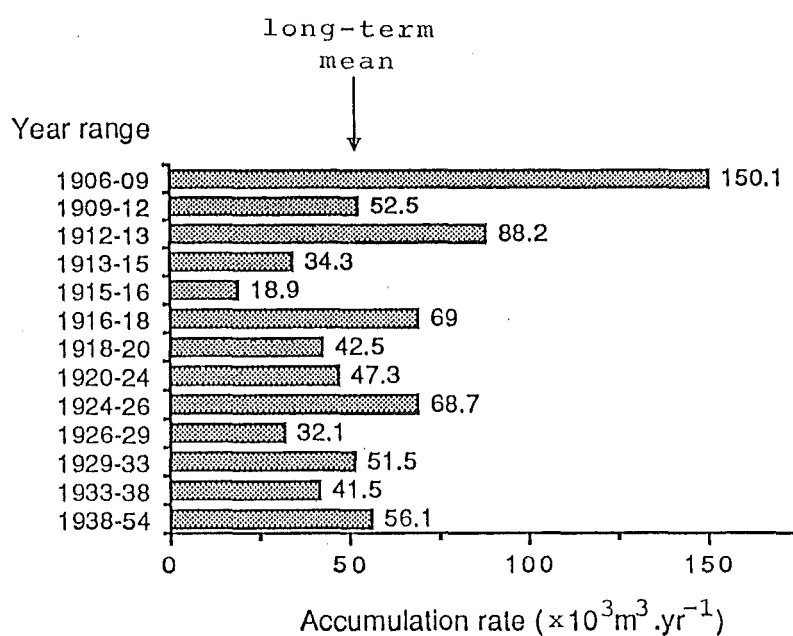


Figure 5.8 Average yearly rates of accumulation at South Beach, Timaru; 1906-1954.

ranges of yearly drift can be estimated. The direction of net drift is always northward over the period of a year, but the potential range of variation in this direction is probably at least an order of magnitude around the mean. Usually, however, the yearly range appears to be within $\pm 25\%$ of the mean, or between about $38,500 \text{ m}^3.\text{yr}^{-1}$ and $64,000 \text{ m}^3.\text{yr}^{-1}$.

5.4.3 Sub-annual variations

Few measurements of the rates of longshore transport over periods of less than a year have been made on sand and gravel beaches despite this being the scale of greatest variability. The wave climate of the South Canterbury coast is noted by Kirk (1980) to have no pronounced seasonality, so therefore the net drift rate does not diverge from the annual mean over regular half-yearly cycles. Conversely, individual and successive storm and swell events can produce large net movements of sediment in both directions alongshore. Although waves from the southeast quadrant dominate the study area, northeasterly waves can prevail for several weeks at a time. An idea of the overall range of drift rate variations over short periods of time can be gained from two specific examples from South Beach. It was mentioned earlier from Kirk (1984) that $26,000 \text{ m}^3$ of coarse material travelled the length of the breakwater during a southerly storm in 1983. Assuming that the total volume was delivered past the northern end of the South Beach foreshore over a typical storm period of 12 hours, the northward rate of transport at this location was a phenomenal

$1.9 \times 10^7 \text{ m}^3.\text{yr}^{-1}$ when expressed in annual terms. This value probably approaches the upper limit of storm wave drift capacity and is a duration limited event.

Counterdrifting caused by weaker northeasterly wave fields occurs at a much lower rate but may persist for longer periods than southerly storms. In a study that will be investigated in the next section, it was found by beach volume measurements that the southward rate of transport over 20 days was equivalent to $37,000 \text{ m}^3.\text{yr}^{-1}$.

Instantaneous and short-term movements of sediment can therefore occur in both directions alongshore, with extreme rates toward the north of at least two orders of magnitude greater than the long-term mean. These opposing motions are caused by changes in the directions and energies of the wave environment, and negate each other to produce net rates over longer periods than are considerably less than the gross rates. The extent to which the dominant northerly drift is counteracted changes each year, and this has a noticeable effect on the annual net rate of drift, which was shown to vary also, by at least an order of magnitude. Remarkably, the high degree of short-term variability does not produce significant changes to the long-term rate, which remains quite constant over time.

5.5 ESTIMATING AND CALIBRATING THE POTENTIAL RATE

A major problem in determining the rate of long-shore transport on the South Canterbury coastal foreshore is that the phenomenon manifests itself in measurable

terms only near the littoral barrier of Timaru Harbour. It occurs elsewhere on the mixed sand and gravel beaches under a similar process-response system, but does not occur at the same rate mainly because of differences in the orientations and wave environments of each location. A possible solution to finding the rates of longshore transport at locations away from Timaru is to determine the potential ability of the different wave environments to transport sediment alongshore.

The longshore energy flux factor, $P_{\ell s}$, was identified in Chapter 2 as a parameter developed on sand beaches for solving the problem in this way. The value of $P_{\ell s}$ is calculated from a number of variables that describe the characteristics of the incident wave energy - the heights, velocities and angles of the approaching waves are the basic determinants of this. These wave characteristics are external variables independent of the foreshore environment itself. Therefore, despite the physical differences between sandy and mixed sand and gravel foreshores, the longshore energy flux into the foreshore can be calculated from the same formulae for both types of beach system.

The dependence of sediment transport on energy flows along a mixed sand and gravel beach has already been affirmed. Hence, as in the sand beach situation, it is assumed here that the relationship between the volume rate of transport, Q , and the longshore energy flux at breaking is positive and linear. It can then be presented in terms of a dimensionless constant, k . The results of Hewson (1977) suggest that a value for k of 1290 is too high for

the South Canterbury foreshore. A more appropriate value has not yet been widely sought in a mixed beach situation, despite the demonstration of its usefulness on sand beaches in other countries. The primary objective of this section is to generate such a value.

To determine the value of k , the magnitudes of the two variables in the equation - Q and $P_{\ell S}$ - must first be known. Reasonably accurate approximations of the longshore component of energy flux can be obtained by various methods, including refraction analyses of deepwater waves (as done by Hewson, 1977), and analyses of shore-based observations. Conversely, the 'true' rate of longshore transport is less easy to establish, and is fully known only under controlled laboratory conditions that seldom reflect the field situation accurately. Because of this, the right-hand side of the equation $Q = (k P_{\ell S})$ can only be calibrated against rate estimates of unknown accuracy that are obtained from other methods.

It is important to realise that the calibration of k can only be done by comparing values of $P_{\ell S}$ and Q that represent the same physical conditions of sediment transport. Ideally, this requires estimates of each to be made for the same time and location. Failing this, assumptions may have to be made to validate their equivalence. Once calibrated in this way to the mixed sand and gravel beach situation, the Energy Flux Method can be more accurately applied to separate but comparable times and locations.

5.5.1 Calibration from previous estimates

The estimates by Hewson (1977) of the longshore energy flux at four locations along the South Canterbury coast require calibration against estimates of the concurrent rates of longshore sediment transport. One of these locations - South Beach - has been the site of four other studies that have given estimates of the longshore transport rates by an alternative method. Each of the authors who have previously measured the shoreline changes updrift of the littoral barrier at Timaru Harbour have been concerned more with the rate of accumulation than with the northward drifting of foreshore sands and gravels that it is mostly caused by. Possibly because of this, the potential use of these values as calibration standards for the Energy Flux Method on mixed sand and gravel beaches has not been well recognised. The values of Q and P_{ls} have thus been presented, but the calibration procedure, although very simple, has been carried out only by Kirk (1984), using slightly different methods. This particular study will be discussed later.

The values for both of the variables can be taken to represent the average long-term conditions at South Beach. They therefore cover the same time period and location, and are able to be compared directly. Two numbers are to be used in this comparison. The first is the average longshore component of energy flux at South Beach, which was found by Hewson (1977) to equal 557 N.s^{-1} (converted from imperial). The second is the volume rate of longshore transport determined from the historic accumulation measurements in the last section, which is

equal to $51,288 \text{ m}^3 \cdot \text{yr}^{-1}$. By inserting these numbers into the equation, $Q = k P_{\ell S}$, a value of 92.1 is obtained for k .

Before this result is utilised further, its true meaning should be made clear. Firstly, the equation relates to the potential ability of the incident wave climate to transport sediment alongshore. This is not necessarily the same as the actual rate, and is usually somewhat higher. In this respect, the use of the equation is likely to overestimate the 'true' rate. Secondly, and in contrast, the value for Q that was used to calibrate k was earlier stated to be a minimum estimate of the longshore transport rate, so that this will cause k to be lower than its 'true' value. The extent to which these two aspects negate one another is impossible to assess. It is therefore not known whether a value of $k = 92.1$ gives an upper or a lower estimate of the longshore transport rate on South Beach. It is likely, however, that it is a reasonably close estimate.

Kirk (1984) has previously performed a calibration for South Beach of the relationship between a longshore transport rate estimate and a measure for the longshore component of wave power. The part of the equation expressing the longshore component of wave power was applied to prevailing wave conditions at South Beach that have been determined by Hastie (1983). Using the formulations that are thought to be appropriate for sand beaches, Kirk (1984) calculated a rate of northward transport into South Beach that "is some 23 times higher than the known historical accumulation rates,...and is thus unrealistic." He then went on to calibrate the formulation against his

estimate of the annual accumulation rate over 104 years, quoted in Table 5.1 as $56,981 \text{ m}^3 \cdot \text{yr}^{-1}$.

In terms of the equation $Q = k P_{\ell s}$, the value of k that was obtained from the above procedure works out to be $1290/23.2 = 55.7$. This is 40% lower again than the calibrated value obtained earlier from other data for South Beach. It is not yet possible to judge which value is closer to the 'true' value.

5.5.2 Calibration from short-term rates

With the objective of reinforcing or refuting the two values for k so far obtained for predicting the longshore transport rates on the mixed sand and gravel foreshore at South Beach, a new approach was followed. As before, estimates of $P_{\ell s}$ and Q were sought for coinciding time periods and locations. So that direct comparisons of the k values could be made, and because the clearest and most readily available estimates of Q are obtained from the sediment volume changes at South Beach, it was decided to undertake the study at this location. Concurrent estimates of $P_{\ell s}$ could then also be obtained from the LEO program that was carried out with the co-operation of the Timaru Harbour Board at the same site. In brief, the method used was a comparison of the estimated average longshore component of energy flux from the LEO program, with foreshore volume changes updrift of the breakwater, as measured by successive beach profile surveys. A schematic plan of the procedure is drawn in Plate 5.2 and this can be followed through the description and analysis that follows.

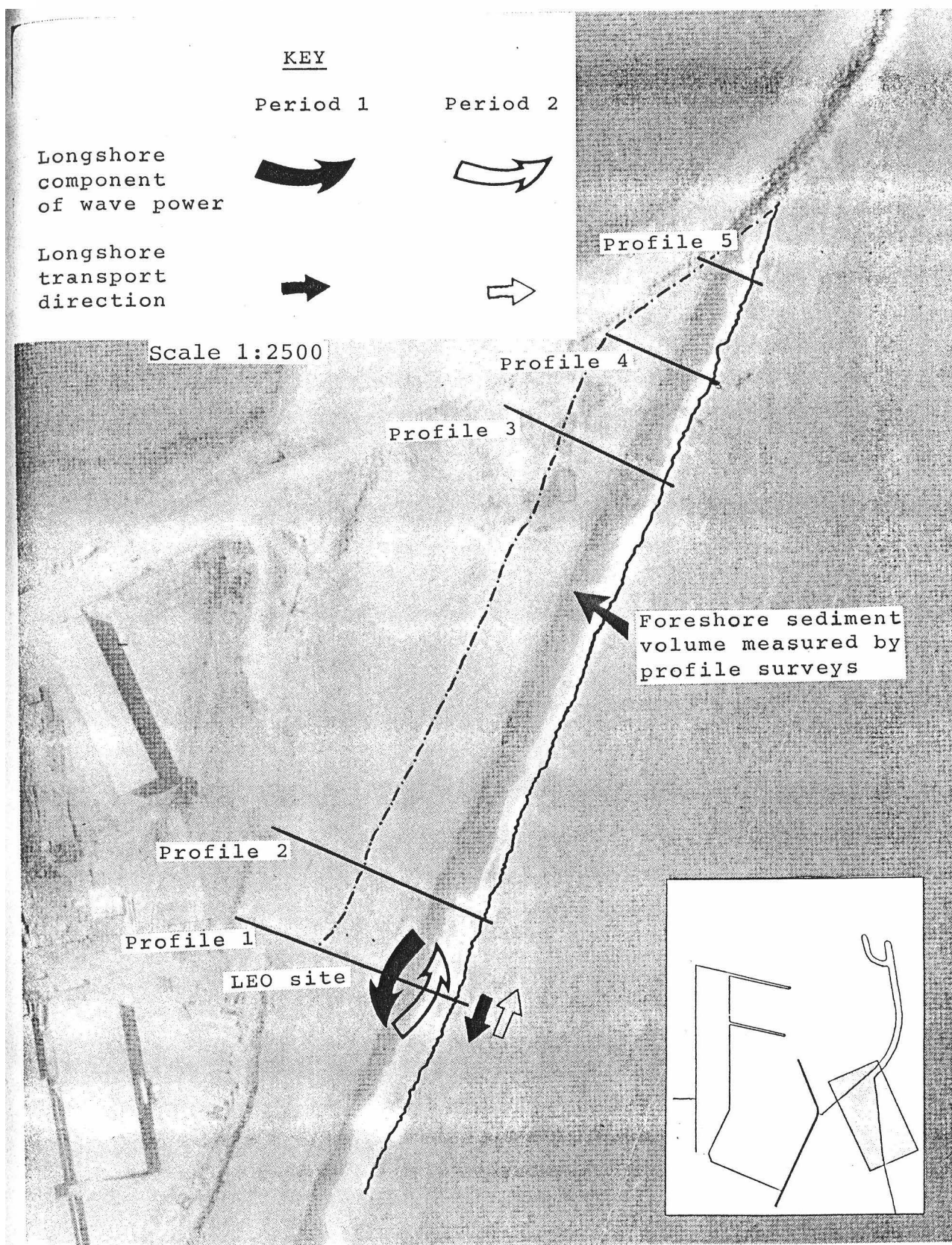


Plate 5.2

Schematic plan of short-term rate estimate procedure, South Beach; 1987.
(Source: 1980 photo, Timaru Harbour Board).

Longshore Energy Flux

The procedures for estimating the longshore energy flux from shore-based wave observations have been very well documented (e.g. Walton, 1980a; Bruno et al, 1981; U.S. Army, 1984). Of primary concern to the present study was the estimates from the LEO program of breaker height and wave approach angle. These variables were used to compute the longshore energy flux factor, $P_{\ell s}$, for each set of daily observations. The formula for this is recalled from equation 2.5:

$$P_{\ell s} = \frac{\rho g}{16} H_b^2 C_b \sin 2 \alpha_b \dots N.s^{-1} \dots 5.2$$

To find the average longshore energy flux over a given period, the mean of all the $P_{\ell s}$ values is calculated. A standard assumption is made here that the observations made for approximately ten minutes each time adequately represent the conditions between the preceding and following observation times (usually one day). This is justified by the knowledge that storm and swell events, which exhibit the greatest variations in wave characteristics, usually last for a period of days, and were therefore seldom missed by daily observations.

For reasons that will become clear, the observations and resulting $P_{\ell s}$ values were separated into two adjoining time periods. Period 1 was over 20 days from January 8 to January 28, 1987, while Period 2 covered the remaining 100 days of the LEO program from January 28 to May 14, 1987. It can be seen from Table 5.2 that these two periods were characterised by quite different wave and foreshore conditions at the observation site on South Beach. The most important difference is between the prevailing wave

Table 5.2 Summary of LEO at South Beach, Timaru over
the two observation periods

	Period 1	Period 2
Time interval (days)	20	100
No. of observations	17	62
Prevailing wave approach (%NE: %SE)	northeast (35:12)	southeast (15:21)
Prevailing water drift direction (%S: %N)	southward (76:24)	northward (29:61)
Mean (std.dev.) breaker height (m)	0.68 (0.91)	0.79 (0.35)
Mean (std.dev.) wave period (s)	5.43 (2.20)	6.69 (1.91)
Modal breaker type	plunge	spill/plunge
Mean (std.dev.) swash length (m)	12.35 (3.52)	18.50 (7.66)
Mean (std.dev.) $P_{\ell s}$ ($N.s^{-1}$)	-2479 (8259)	1922 (8471)

directions, shown clearly by the percentage frequencies in the table. It is evident from this that oblique waves approached mainly from the northeast quadrant in the first period, and from the southeast in Period 2. The waves that were recorded as approaching perpendicular to the shore were also likely to have some degree of obliqueness, and the difference between the two periods is made more obvious by the high asymmetry of the wave-dependant water drift directions. It can also be seen that the other control on the value of $P_{\ell s}$ - the breaker height - was approximately the same over the two periods, the means differing by only 0.1 m.

Listed at the bottom of Table 5.2 are the computed values for the mean longshore energy fluxes for the two periods. These values give the average rate of energy flow (in $N.s^{-1}$) through a plane normal to the shore at the LEO site. It can be seen from the values in Table 5.2 and the plan in Plate 5.2 that the average energy flux was southward away from the breakwater over the first period, and north toward the breakwater over the second period. The absolute magnitudes of these average energy flows were comparable, however.

Volume rate of Transport

The measurement of Q for the left side of the potential rate function was made at South Beach under the 'littoral barrier' assumptions for the Eastern Extension Mole that were justified earlier. The rate of longshore sediment transport was assumed to be represented by foreshore volume changes updrift of the mole. To ensure that the values of P_{LS} and Q would represent the same environmental conditions, the volume changes were measured at the same time and from the same point updrift of the mole as the LEO program.

The net volume changes downdrift of the LEO site as far as the breakwater end of the beach (a distance of almost 350 m) were calculated from three repeated surveys of five profile lines along the beach (shown in Plate 5.2, numbered 1 to 5 northwards). The surveys were done on January 8, January 28 and May 14; hence the corresponding division of the LEO recordings. Three main problems were encountered in the undertaking of the beach surveys.

The first involved the presence of a gravel extraction pit within the surveyed area. An initial fear that the morphological (volume) changes caused by over-washing into and extraction from the pit would not be measurable from profile surveys was allayed to some degree by the fact that significant volumes of overwash did not occur during the study period. The amount that did occur was indeterminable, but almost certainly negligible. The second and third problems also concerned the gravel extraction works. The regular disturbance of the back-shore surface over a large area in the middle of the surveyed beach precluded the establishment of a permanent profile survey marker along 190 m of the shoreline. In conjunction with this, the final problem was that the marker for Profile 2 was unfortunately bulldozed out following the second set of surveys, despite its siting among vegetation well back from the gravel surface. It will be shown later that the limited number of survey lines in the southern half of the area is unlikely to have had a significant effect on the final results.

The change in foreshore volume within the surveyed area was calculated by measuring the areal changes beneath each profile and interpolating from these along the whole length of beach. The changes were measured to a depth of -1 m AMSL, for the reasons stated in the previous section concerning the depth of the foreshore. The sediment volume changes at the profile sites along the beach are shown in Figure 5.9 for the two periods surveyed. Within the surveyed area, the greatest changes occurred within 100 m of the breakwater end of the beach, whereas changes south of Profile 3 were small and fairly constant along-

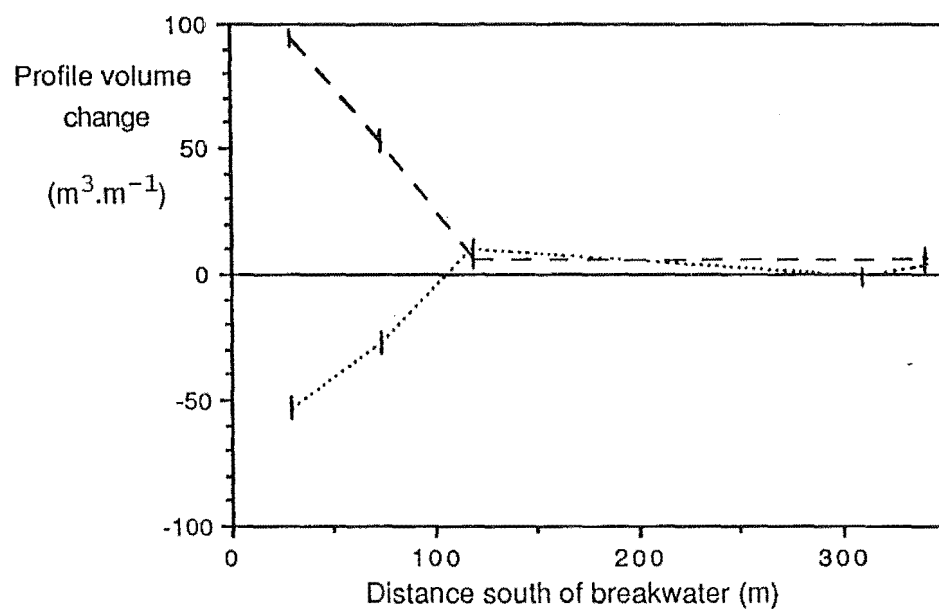


Figure 5.9 Short-term volume changes at South Beach, 1987.

..... Period 1
- - - Period 2

shore. This was caused by the effect of the littoral barrier at the northern end. During the first intersurvey period, the prevailing waves from the northeast moved large amounts of foreshore material southward over the whole beach. Because there was no supply of sediment into the northern end of the beach, the area of foreshore adjacent to this end suffered a net sediment budget deficit. Further south, the foreshore was adequately supplied with the material removed from the northern end and so incurred little net change in volume. During the second period, sediment was moved toward the north by the prevailing southerly waves. It can be seen from the graph in Figure 5.9 that this caused volume increases at the northern profiles. Large volumes of material were delivered to the northern end of the beach, but could not be moved further, due to the trapping effect of the mole.

The net foreshore volume changes between the LEO site (Profile 1) and the northern end of the foreshore (≈ 30 m north of Profile 5) are represented for each period by the areas enclosed by the line graphs in Figure 5.9 with reference to the zero line. The calculated changes were converted to an annual rate of volume increase, to give $36,964 \text{ m}^3.\text{yr}^{-1}$ for Period 1 and $26,628 \text{ m}^3.\text{yr}^{-1}$ for Period 2. Under the littoral barrier assumption that sediment transfers into the area of foreshore covered by the profile surveys occur totally through the updrift end (at Profile 1), the foreshore volume changes become a measure of the rate of longshore transport past this profile line. With the imperfect barrier conditions thought to occur at South Beach, they are taken as a minimum estimate of the transport rate.

5.5.3 A new value for k

The four-month study at South Beach has produced two sets of estimates for identical times and locations of the longshore energy flux ($P_{\ell S}$) and the volume rate of longshore transport (Q). By inserting these values into the equation, $Q = k P_{\ell S}$, it is a simple matter to find two independently-derived values for the dimensionless constant, k . These two numbers are listed in Table 5.3, along with the two acquired in the previous section.

Table 5.3 Values for k derived from South Beach data

Sources	k
U.S. Army (1984) (sandy beaches)	1290
$P_{\ell S}$; Hewson (1977):	
Q ; present study (Section 5.4)	92.1
Kirk (1984)	55.7
Present study, Period 1	14.9
Present study, Period 2	13.8

Two important aspects of these results are patently obvious. The first is that all of the k values for South Beach are more than an order of magnitude lower than the value regularly used in the abundant literature on sand beach transport rates. A suggestion that can be advanced from this is that the efficiency of incident waves to transport volumes of material along the South Beach foreshore is less than that on sand beaches, also by an order of magnitude. This seems quite plausible, since although the power of the swash processes on a mixed sand and gravel beach is more intense than the surf zone

circulation of a sand beach, it covers a smaller area of foreshore and is much more intermittent. In addition, the constituent particles are less movable on account of their sizes.

The second notable aspect of Table 5.3 is the degree of variability among the four estimates of k for South Beach. The potential sources of this variation are numerous and difficult to verify, but are most likely to lie in the methods and accuracies of data acquisition, and in the time scales used for estimating $P_{\ell S}$ and Q . This view is supported by the relative similarity of the two k values obtained from each of the two basic methods. In addition, the two lower k values may be due to the poorer representation of high-energy storm conditions by those particular studies. The transporting effectiveness of storm waves at South Beach was demonstrated earlier to be disproportionately high in relation to their breaker heights, so that the prevalence of less efficient swell waves in the short term studies may explain the lower values obtained for k . If this is the case, then the wave power formula may have a far more complex relationship with the transport rate than is assumed here. Nevertheless, it is noted by Smith and Piggott (1987) that an order-of-magnitude variability of the rate estimate is all that is presently possible on many intensively studied sand beaches, and so the result here is considered to be acceptable in the present state of knowledge.

The new values for k have so far been applied only to the conditions occurring on the mixed sand and gravel foreshore at South Beach. The fundamental purpose of the Energy Flux Method - to predict the transport rate from a

known wave climate when other methods are impracticable - has not yet been fulfilled. For this purpose, and because of the physical uniformity of mixed sand and gravel beach systems, it is justifiable to assume that the relationship between the volume rate of transport and the longshore energy flux is of the same magnitude at all locations. It must therefore be possible to estimate the longshore transport rate at other sites where $P_{\ell s}$ is known, by using a constant value for k of between approximately 13.8 and 92.1. The lower value may give a more appropriate estimate for the lower energy type of conditions on which it was based. If long-term average rates are required, the higher of these two values is likely to provide a more accurate estimate. By this means, it is possible to gain a better approximation for each of the locations listed in Table 5.1, and these are given in the table below. These estimates are calculated from the same wave power magnitudes, but have a much greater reliability than the original estimates quoted from Hewson (1977). Moreover, by using the calibrated k values, wave refraction analysis and other procedures for evaluating the longshore component of wave power can now yield a more accurate range of estimates for the longshore transport rates on sand and gravel foreshores at any point along the coast.

Table 5.4 Revised estimates of potential transport rates,
using $k = 92.1$ for locations listed in Table 5.1

Location	Longshore transport rate ($\text{m}^3 \cdot \text{yr}^{-1}$)
South Beach (reference site)	51,288
Pareora	-51,380
Waihao R.	235,630
Waitaki R.	80,569

5.6 SUMMARY

Longshore sediment transport on the foreshore of the South Canterbury mixed sand and gravel beach system occurs at a rate that is variable in both time and space. Previous studies of the phenomenon have clearly identified the northward direction of the long-term net drift indicated by a number of asymmetrical features of the process-response environment. The rates of these movements have been examined only over very long time periods (up to a century) and mostly from only the one location at South Beach. From measurements of the overall rate of accumulation updrift of the littoral barrier at Timaru Harbour since 1878, estimates of the net rate of longshore sediment transport ranging from $51,288 \text{ m}^3 \cdot \text{yr}^{-1}$ (this study) to $87,500 \text{ m}^3 \cdot \text{yr}^{-1}$ (McIntyre, 1958) have been stated or implied. However, the past estimates have strictly applied only to the long term average rate at South Beach, and cannot be justifiably maintained to reflect the true rates at other times and locations.

This chapter has fulfilled the needs for a more diverse methodological base and for an evaluation of the temporal and spatial variabilities of the drift rates along the South Canterbury foreshore. It has been found that the long-term trend is strongly linear, but that significant and irregular fluctuations around the mean do occur at annual and sub-annual time scales. These seem to be mainly due to changes in the approach and energy of the prevailing wave environment, which can produce opposing directions of sediment movement, and rates that are several hundred times greater than the mean.

The estimation of longshore transport rates on open-coast beaches such as those occurring along most of the South Canterbury coastline is made difficult by the unrestricted sediment transfers through both ends of the beach. Net longshore transport rates are therefore not clearly expressed by morphological changes and the most appropriate conventional approach is the 'Energy Flux' method for measuring the potential ability of deepwater waves entering the foreshore to transport sediment along-shore. Because the sand beach formulation of this relationship clearly overestimates the 'true' value, the equation was calibrated by two methods against foreshore sediment volume changes at South Beach. These gave two rate estimates that are thought to be suitable for long-term and low energy conditions, respectively. Thus, the ability to predict the temporal and spatial ranges of longshore sediment transport rates on mixed sand and gravel beaches has been improved.

CHAPTER 6

LONGSHORE TRANSPORT FROM SHORE MORPHOLOGY - A NEW METHOD

6.1 INTRODUCTION

It has been demonstrated in previous chapters that the phenomenon of longshore sediment transport is inconstant across the four dimensions of the mixed sand and gravel foreshore environment: depth, width, length and time. Studies of the depth of disturbance, the shore-normal subzonation, and the transport rate variations both along the coast and through time have examined the variability of longshore transport within each of the four dimensions, mostly in isolation from the other three. The integration of all four dimensions has not yet been accomplished in this investigation.

Of particular importance to coastal dynamics are the relationships between the temporal and spatial aspects of longshore sediment transport. Longshore transport necessarily involves movements of beach material simultaneously through both time and space. Furthermore, these two components of motion are fundamental to the rates of longshore transport, since rates are expressed in units of space (volume or distance) over time. The rates of motion have been shown to vary in both of these dimensions, but no single method for determining long-term rates has been able to demonstrate this dual variability on its own. For instance, the accumulation rates at South Beach

(Section 5.4) gave an indication of the temporal variability, but only for that one location in space. Conversely, calculations from refraction analysis (Section 5.5), showed that transport rates vary along-shore, but they cannot provide evidence of how these rates change over time. A method that integrates the spatial and temporal aspects of sediment motion within a single framework for analysis should enable a greater understanding of the patterns and rates of longshore transport. The primary objective of this chapter is to develop a method that can accommodate variations in all four dimensions, and that may inspire some overall perspectives on sediment transport along the South Canterbury foreshore.

6.2 METHODS

A combined analysis of the four dimensions can be made only by an examination of changes in the three dimensional morphology of the shore over time. Shore morphology can be defined as the pattern of distribution of the sediment volume. Following this it can be stated that changes in shore morphology over time represent movements of sediment volume through space. An analysis of such changes can therefore be of use to gaining a better understanding of the process-response environment in which sediment transport occurs.

The most suitable technique for examining the four dimensions of a foreshore is by repeated surveys of a series of beach profiles along the coast. The depth and

width of the shore morphology are shown within each profile, while the alongshore component can be determined by making comparisons between profile lines. Temporal aspects are recognised through the repetition of the surveys.

By far the most comprehensive beach survey program on the South Canterbury coast has been undertaken by the South Canterbury Catchment Board since 1977. Data have been acquired over 10 years from 19 profile lines between Waitaki River and Timaru and were used for the present study. The locations of these lines are shown in Figure 6.1. The lines range from 0.42 km to 5.97 km apart and have been surveyed on average at approximately yearly intervals. The raw data from each line comprised maximum heights above mean sea level, widths, and volumes above 1 m above MSL (AMSL) of the beach profile, and the time of each survey after a base date (6-2-77).

Only the beach volumes (i.e. profile areas) were used in the analysis, since it is possible for the width and/or the height not to respond to variations, or net transfers of sediment alongshore.

Figure 6.2 demonstrates an instance in which the shore morphology (sediment volume) is inconstant alongshore, but neither the maximum height nor the width of the beach are altered. Such a situation may be common on a mixed sand and gravel foreshore, since the seaward boundary is steep and semi-stable, whereas the mid-foreshore face is the main subzone of sediment movements and it exhibits the greatest changes in the profile morphology.

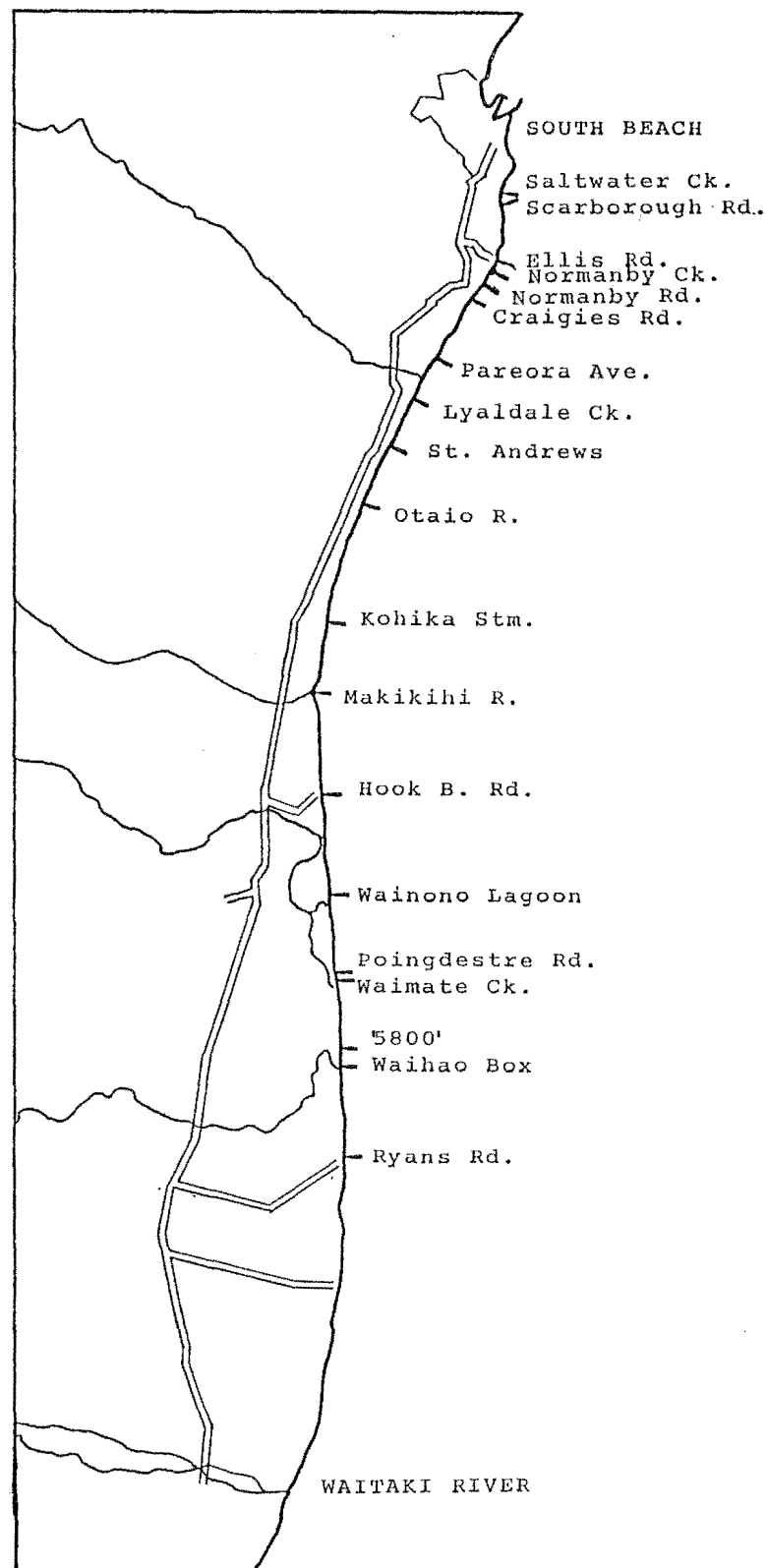


Figure 6.1 Profile locations and names, Waitaki River to Timaru.

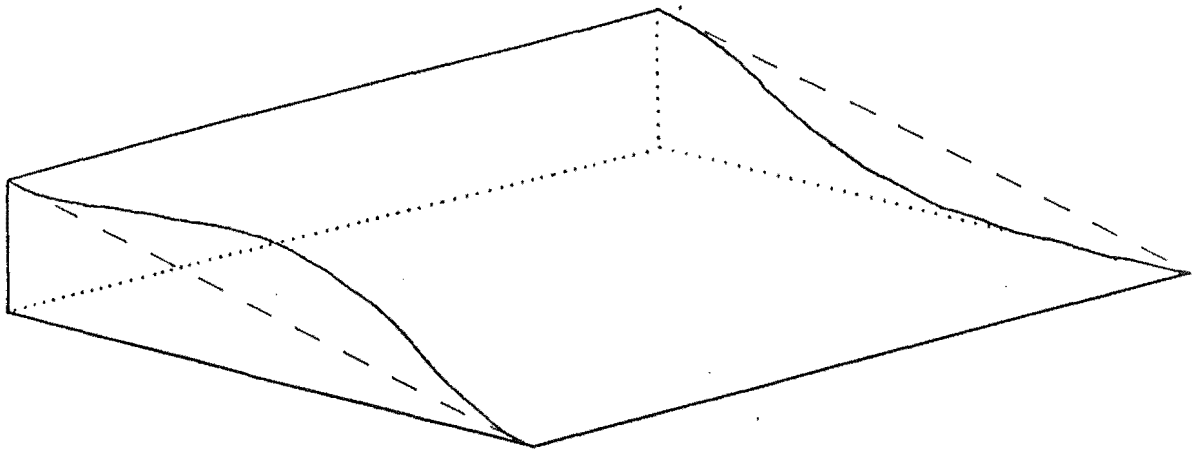


Figure 6.2 An example of a beach with a varying volume alongshore, but constant maximum height and width.

To allow comparisons between profiles with different total volumes the data were standardised using the formula;

$$B_z = (B_t - B_x^-) / B_x^- \quad \dots 6.1$$

where B_z is the standardised profile volume,

B_x^- is the mean of measured volumes at a given profile ($m^3 \cdot 100m^{-1}$ above 1m AMSL)

B_t is the volume at time t ($m^3 \cdot 100m^{-1}$ above 1m AMSL)

From this formula, it can be seen that below and above average volumes at a profile are assigned negative and positive standardised values respectively. Average volumes have a value of $B_z = 0$. The changes in the standardised beach volumes over the intersurvey periods were then interpolated by computer using the 'Stineman' method, to avoid personal biases in the analysis and to yield smooth curves having objectively located maxima and minima.

6.3 FORESHORE VOLUME FLUCTUATIONS

The results of the procedure are shown in Figure 6.3. Each horizontal line in the diagram shows the location of a profile along the coast, which remains fixed over the ten year period. The horizontal lines also represent the measured means of the sediment volume for their respective profiles. For each profile, the changes in the sediment volume over time are shown as curves fluctuating around the measured mean. For example, the southernmost profile line is 14.5 km north of the Waitaki River and is shown to have retained a volume above the measured average for most of the ten year period, but to have fallen below

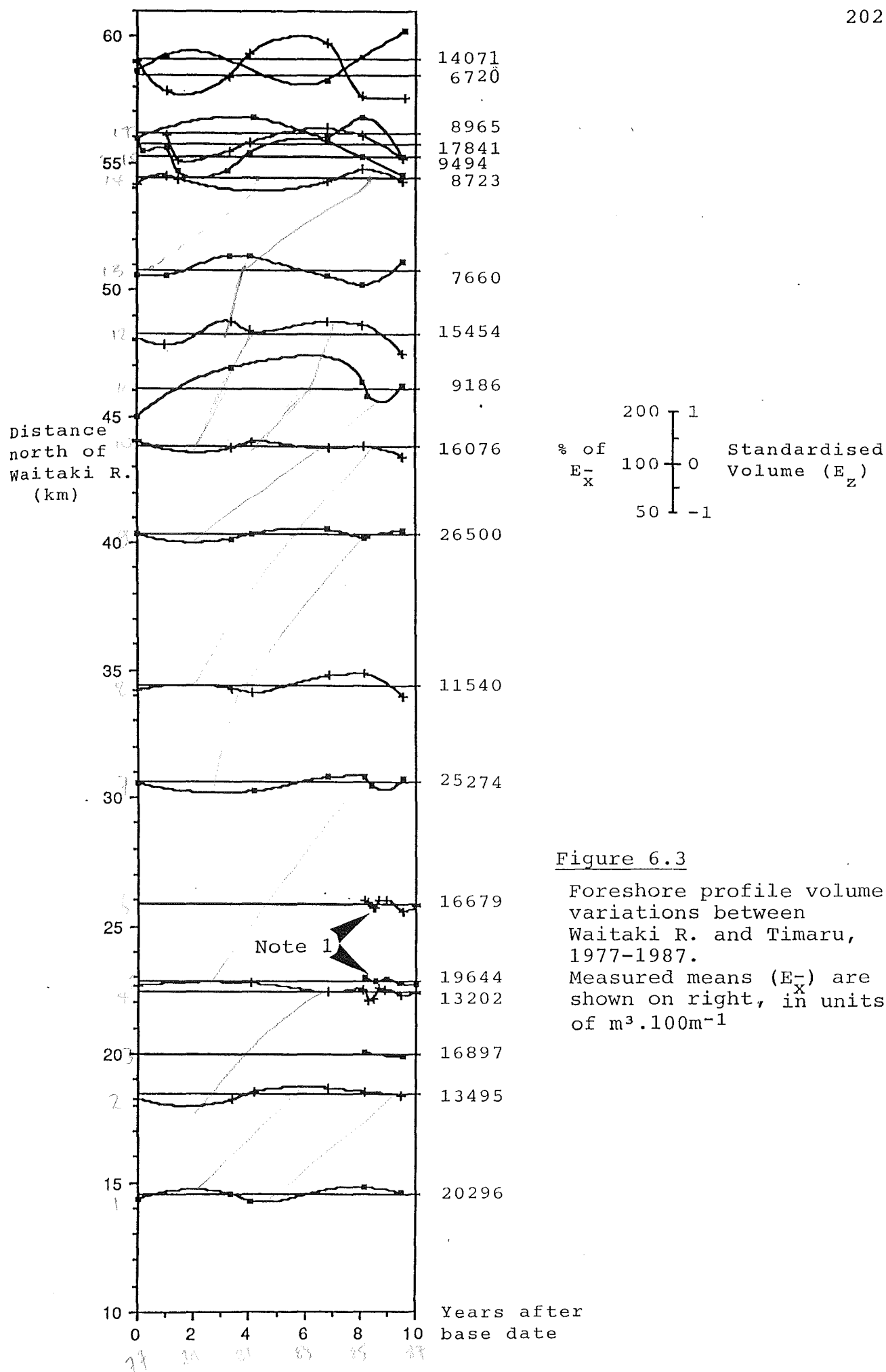


Figure 6.3

Foreshore profile volume variations between Waitaki R. and Timaru, 1977-1987.

Measured means (E_x) are shown on right, in units of $m^3 \cdot 100m^{-1}$

this level between 1981 and 1983 (4-6 years after the base date).

The interpolations in the diag only represent long-term trends or fl several years as a result of the rela surveys. Short-term fluctuations due and swell conditions that are superimposed on the long-term changes can have some effect on the correctness of the interpolations. Examples of these effects can be seen at Note 1 in Figure 6.3.

In terms of surveyed volumes, short-term changes are of a lesser amplitude by greater than 40% of the average maximum range of volumes measured at each profile over the 10-year period, so that short-term variations are among the smallest fluctuations of all those shown by the interpolations. Short-term changes can therefore be assumed to have some influence on the accuracy of the interpolation, but they do not account for the total variation shown.

It can be clearly seen that the volume changes are not paralleled through all of the profiles. It is important to note here that the amplitudes of the fluctuations should not be compared between profiles, since they are standardised only to individual profile sites over time. Differences between absolute volume changes will be discussed in a later section. The positions of the peaks and troughs of the curves alongshore and over time can be directly compared, however, as indications of changes from accretion of the profile (rising curve) to erosion (falling curve), and vice versa. The curves in Figure 6.3

show that while some profiles experienced accretion over several years, others underwent erosion.

6.4 IDENTIFYING THE CAUSE

To interpret the pattern shown on Figure 6.3, an important objective is to identify the processes that cause it. Clearly, the volume changes must involve fluctuating rates of sediment transfer into and out of the profile sections. Such changes have been shown in previous chapters to result from variable input factors of energy and/or materials. Variations in the incident deepwater wave energy cannot explain the pattern, since these should produce broadly similar in-phase profile responses along the whole of the South Canterbury coast for a given time interval. Instead, localised fluctuations in the available supply of sediment to the profile sections are the probable cause of the observed volume changes. Since the offshore sediment supply on a mixed sand and gravel beach is negligible, the variable supplies of sediment that produce the volume changes are almost certainly from alongshore. The primary hypothesis to be maintained for the remainder of this chapter is thus that the patterns shown in Figure 6.3 can be explained as localised movements of fluctuating volumes of material drifting past each profile line.

Above average volumes of drift can be imagined as being 'slugs' of material, introduced to the foreshore perhaps by an episodic input from a river or eroding cliff. Several other causes of the formation of these slugs are possible but will not be explored in this study.

For example, the mouth migration of the Waitaki River, or alongshore grain size variations such as those noted by McLean (1970) on the Kaikoura coast, may be related to slug formation. It is worth noting however, that an identical analysis compiled for the section of coast between Washdyke Lagoon and Opihi River revealed no discernable pattern of slug movement alongshore. It is thought that this may be related to the absence of point sources of material to the south of that section of coast. Such sources may be a precondition for the initial formation of a slug of sediment on the foreshore.

Slug inputs become an excess of sediment above the base volume originally transported alongshore by coastal processes. Figure 6.4 shows that if the bulk of the materials comprising the slug move alongshore at approximately equal rates, the 'protruding' morphology (excess volume) of the slug will persist while also migrating at that rate. For this reason, the migration of identifiable beach forms over time can be used as a measure of the net rate of transport of their constituent materials.

It was remarked in the previous chapter that migrating beach forms have been observed on sand beaches, but that their possible occurrence on mixed sand and gravel foreshores has not yet been affirmed. The two-dimensional plan view of the South Canterbury coast made by Gibb and Adams (1982) failed to reveal such patterns and the authors did not examine the possibility that morphologic variations mostly occur in the vertical dimensions of the beach. This may in fact be likely, since the seaward boundary of the South Canterbury foreshore is steep and

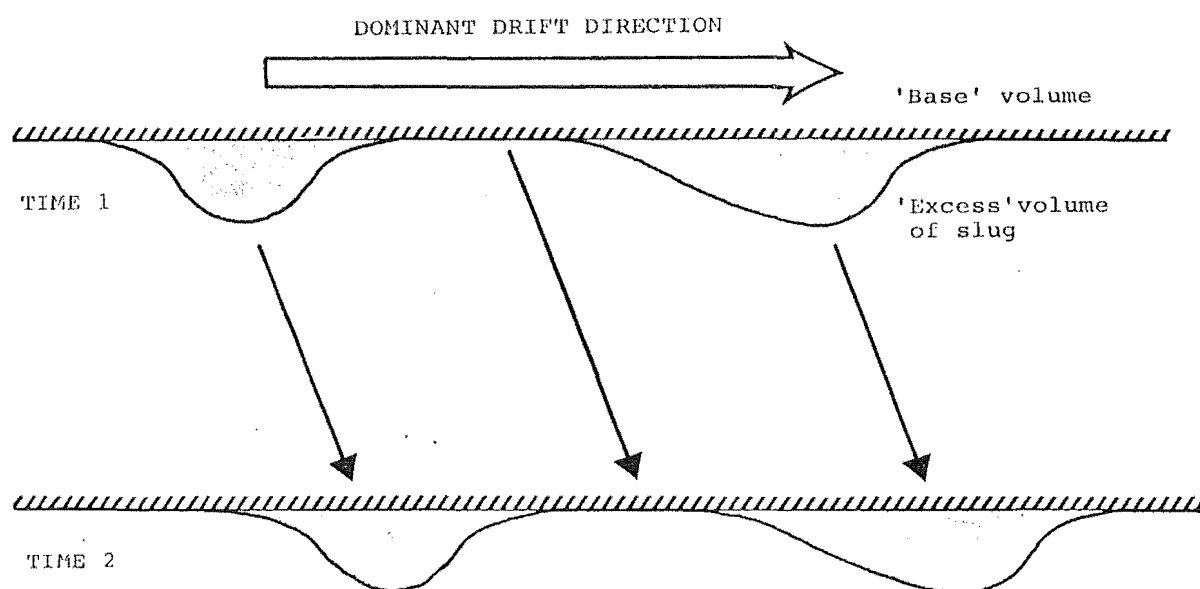


Figure 6.4 The translation of a 'slug' of sediment alongshore.

stable, whereas the mid-foreshore face is the main subzone of sediment movements and exhibits the greatest changes in the profile morphology. Any attempt to identify variations in morphology on a mixed beach should therefore firstly examine the beach in profile.

6.4.1 Linking the Patterns

If morphologic translations occur along the South Canterbury foreshore in the manner stated, then it should be evident from Figure 6.3 as a movement of peak volumes (and intervening troughs) from one profile line to the adjacent line in the direction of drift. Linkages can obviously be made very easily between profiles in this way, because each profile in the diagram has troughs and peaks. Many or all of the possible linkages may not be valid, however. The argument in favour of slug movements is strengthened only if a pattern of linkages can be found that fits what is presently known about longshore transport on the South Canterbury coast. Firstly, the linkages must indicate a general northward movement over time, since this is the known direction of drift. Secondly, the rate of movement (measured as the time taken to move from one profile to another) must be realistic and comparable to the rates of movement suggested by previously used methods.

The velocities at which the foreshore morphology ('slugs') are translated alongshore (denoted as V_m , in units of m.yr^{-1}) are in different units from those used in previous exercises, and so they cannot be directly compared to other values. However, it is recalled from Chapter 2 that the volume rate of sediment movement (Q)

can be converted to a velocity (V_s) by regarding the rate as a discharge at a point and applying the formula;

$$Q = A.V_s \quad \dots 5.2$$

The cross-sectional area of the active beach was earlier estimated for long-term movements of material at South Beach to the 46.25 m^2 . The value of Q has also been estimated for South Beach ($51,288 \text{ m}^3.\text{yr}^{-1}$), so that the average net velocity of a particle or mass of particles along the coast in the long-term is estimated to be $1,109 \text{ m.yr}^{-1}$. In addition, the annual variability of the rates was shown to be $\pm 25\%$ of the mean, which implies a range of average annual velocities from 832 to $1,386 \text{ m.yr}^{-1}$. Since it is assumed here that 'slugs' migrate alongshore as collective volumes of sediment, it is likely that they move at approximately this rate at South Beach, and at similar rates elsewhere along the coast.

With these basic guidelines, the linking of the peaks and troughs of the adjacent profiles shown in Figure 6.3 can be attempted. Linkages are most likely to be correct representations of alongshore movements of 'slugs' if they signify rates of motion that approximate the velocities given above. Figure 6.5 shows the linkages that most closely describe such rates. The rates of movement between profiles can be measured from the gradient of the linkage lines, since they are equal to the distances moved (y-axis) divided by the time taken (x-axis). Steep linkage gradients therefore indicate fast rates of slug translation, and this is shown by the key that accompanies the figure. The measured velocities implied by each linkage are included within the diagram.

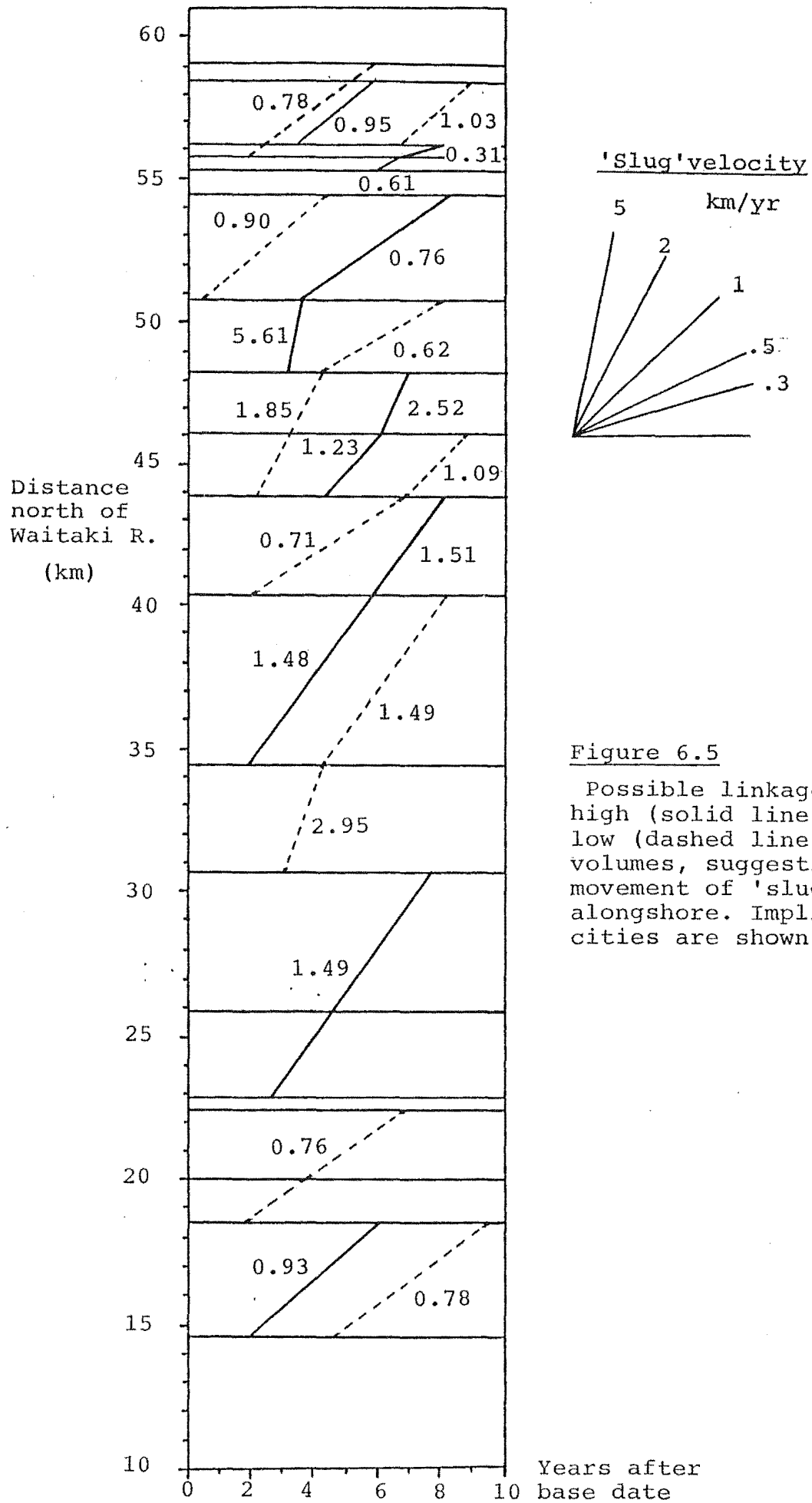


Figure 6.5

Possible linkages of high (solid lines) and low (dashed lines) profile volumes, suggesting a movement of 'slugs' alongshore. Implied velocities are shown in km/yr

The velocities shown for the northern end of the coast near South Beach are very close to the average rate of $1,100 \text{ m.yr}^{-1}$ that was estimated from the accumulation updrift of the breakwater. This correlation is the first major point of evidence supporting the hypothesis that the morphologic changes are due to slug movements alongshore. To provide further evidence, it is necessary to assume here that the most probable linkages that are shown in Figure 6.5 are in fact correct. The nature of the slug movements through time and space can then be examined, and assessments made to accept or reject the hypothesis. If the conclusions arrived at are shown to agree with logical reasoning, then this will strengthen the possibility that sediment transport can occur as collective movements of beach material along the foreshore. Two major aspects that will be examined here are the velocities of movement and the magnitudes of the volume fluctuations.

6.4.2 Rates of Slug Movement

The linkages drawn in Figure 6.5 demonstrate the variability of the rates of slug motion through time and space. It can be seen that the range of mean velocities between profiles was from 0.3 to 5.61 km.yr^{-1} . The apparent differences are most likely to be caused by equivalent variations in the incident wave environments. Periods or locations characterised by oblique or high energy waves would be expected to exhibit rapid slug movements.

To examine the variations of the velocities of slug movement along the coast, mean velocities over the ten

years were calculated from the linkages shown, for the sections of beach between each profile. The rates obtained are plotted in Figure 6.6a. A high degree of variability is obvious, and although a cyclical pattern is apparent, no logical reason can explain why the longshore variations in the rates of movement should necessarily be regular. Instead, an alternative explanation with a physically reasonable basis must be sought.

The wave environment of the South Canterbury coast is a major physical control on the movement of sediment alongshore. It has been shown earlier, and is expressed in the Energy Flux equation, that the wave power at the shoreline and the longshore component of energy flux are the two factors that most affect the rate of longshore drift. Two parameters describing these factors - the refraction coefficient (K_b) and the angle of wave approach (α_b) - can be determined from refraction analysis for all sections of the coast. Refraction coefficients provide a measure of the dispersal of the incident wave energy along a length of coast, and thus also of the level of total energy flux at any location, relative to the deepwater wave energy. The angle of wave approach determines the component of energy flux that is directed parallel to the shore. Both of these parameters should therefore be expected to have a positive relationship with the rates of sediment transport and slug movement.

Although waves from all directions can produce movements of material alongshore, the prevailing southeast waves of the South Canterbury coast have an especially strong effect on the rate of foreshore sediment transport

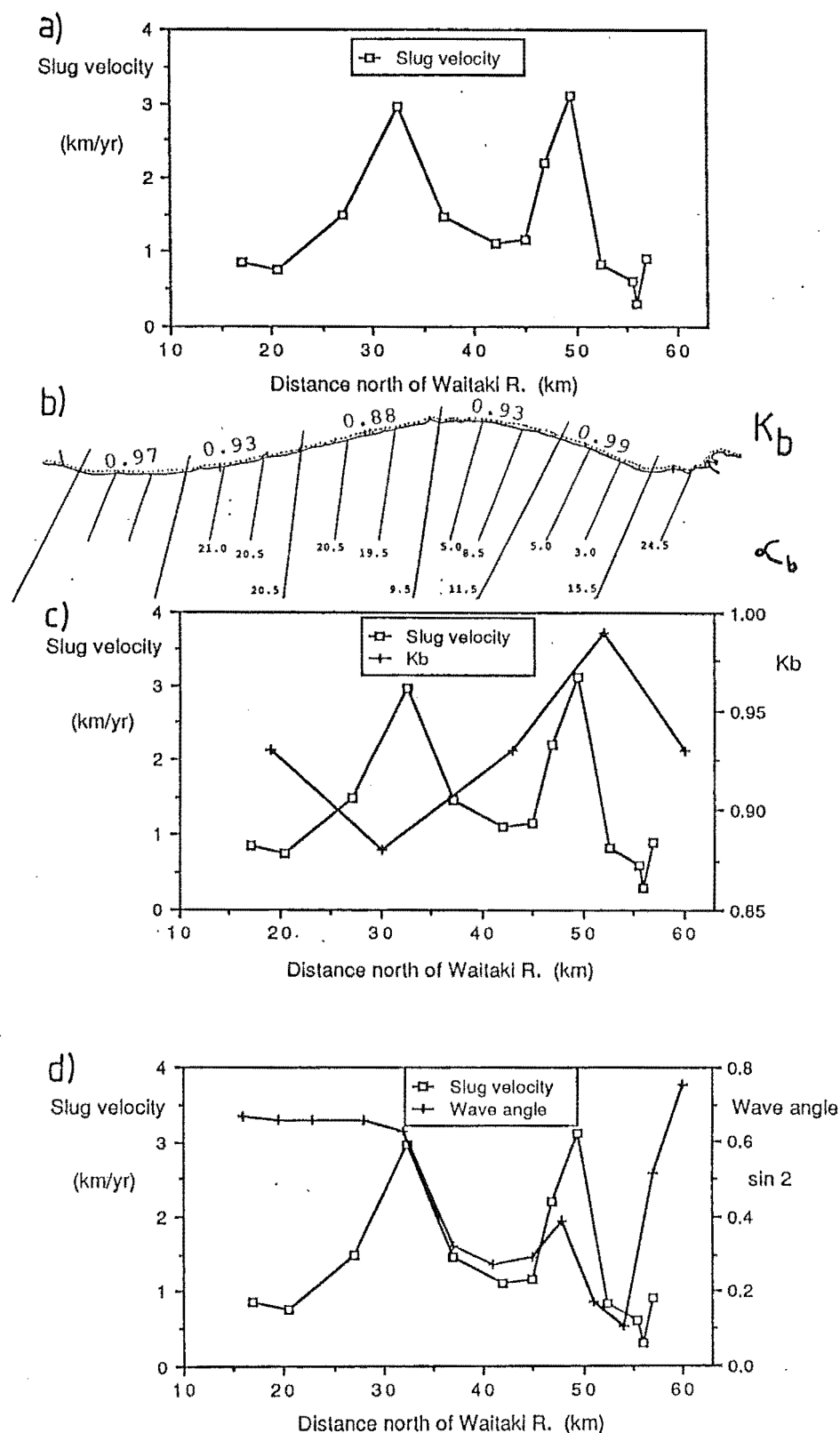


Figure 6.6 Velocities of slug movement alongshore.
 (a) Average slug velocities along the South Canterbury coast.
 (b) Outline of the coast, showing southeast wave angles and refraction coefficients (K_b) (after Hewson, 1977).
 (c) Relationship between slug velocity and K_b of southeast waves at the shore.
 (d) Relationship between slug velocity and approach angle of southeast waves at the shore.

due to their oblique approach and typically high energy levels. Values of K_b and $\sin 2\alpha_b$ associated with deep-water waves from the southeast were obtained from Figure 5.1 and are shown in Figure 6.6b for locations along the coast. These values are overlaid on to the measured slug velocities in Figures 6.6c and d. Several aspects of these two diagrams are worthy of attention.

Although the few data points may hide local variations, it can be seen that the refraction coefficients of the prevailing waves present a quite poor relationship with the rate of slug migration. The correlation is positive over less than one-third of the 40 km in total. The wave angle, however, shows a very close positive relationship along more than half of the coast.

While still assuming that the measured slug velocities correctly represent the patterns and rates of movement, these results suggest that the angle of wave approach has a far greater control than the level of incident energy, over the rate of movement at any location. It should be remembered that this control might only relate to the prevailing southeast waves. Other waves refract differently and produce different rates of movement, but are less significant in the long term. Thus, they do not influence the rate of movement to the extent of the prevailing waves, but are certainly able to have some effect. The greatest discrepancy of Figure 6.6d may be due to such an effect. The slug velocities in the southern section (15-30 km north of Waitaki River) are around 1 km.yr^{-1} , which is about 2.5 km.yr^{-1} slower than expected for the associated wave angle, possibly

because the region is sheltered to some degree from the often stormy southerly waves.

An interesting application of these results is to determine the time taken for slugs (and beach sediment generally) to move from a source to a designated location downdrift. It may be useful to know, for example, the time at which sections of the coast may become affected by the supposed reduction in the sediment output of the Waitaki River caused by dam construction since 1934 (Young and Jowett, 1982). The approximate time taken for a volume of material to move from the Waitaki River to South Beach at Timaru (63 km) was calculated from the slug velocities shown in Figure 6.6a (extrapolating for the southern 14 km) to be 44.0 years. Using the highest slug velocities found for each section of coast, a minimum time of 40.6 years was obtained. Similarly, a maximum time taken was estimated from the lowest velocities to be 51.3 years. These results give an overall average for the longshore transport velocities (V_s) along the whole of the coast of 1.4 km.yr^{-1} , with a range from 1.2 to 1.5 km.yr^{-1} .

Variations in the rate of slug movement over time can also be determined by using this general approach. Such assessments are restricted in the present study because of the time span covered, since ten years appears to be sufficient only for the passage of fewer than two slugs across any given profile line. Nevertheless, the most suitable way to assess changes over time is to compare the velocities implied by each linkage between two profile lines. Applying this method to the present data (in Figure 6.5) was expected to give results that

show a decrease in velocity over the 10-year period, in accordance with the known occurrences of major southerly storms over the earlier years of the study period.

Instead, inconclusive results were obtained, and these are shown in Figure 6.7. Of the eight sections of beach that were crossed by at least two linkages over the ten years, four had higher velocities in the earlier part of the period as expected, with one other having virtually the same velocity for the two linkages. This result by no means proves the assertion that sediment sometimes moves along the coast in 'slugs', but it certainly does not go against the hypothesis. A longer period of records and a closer examination of concurrent wave conditions may provide a greater insight.

6.5 EFFECTS ON SHORE MORPHOLOGY

A stable sediment budget and the maintenance of an equilibrium profile and shore morphology are dependent on a constant balance between the inputs and outputs of all sections of beach. Since the collective movements of sediment in the form of slugs produces inconstant supplies of beach material from alongshore, the potential effects of such phenomena on the foreshore environment may be considerable. The nature and magnitudes of these effects at any location depends mostly on the size of the slug and the duration of influence. These two factors will be ascertained prior to discussing the morphological implications of slug movement as a mechanism of longshore sediment transport.

The method that was used to measure the size range and duration of the fluctuating volumes is shown in

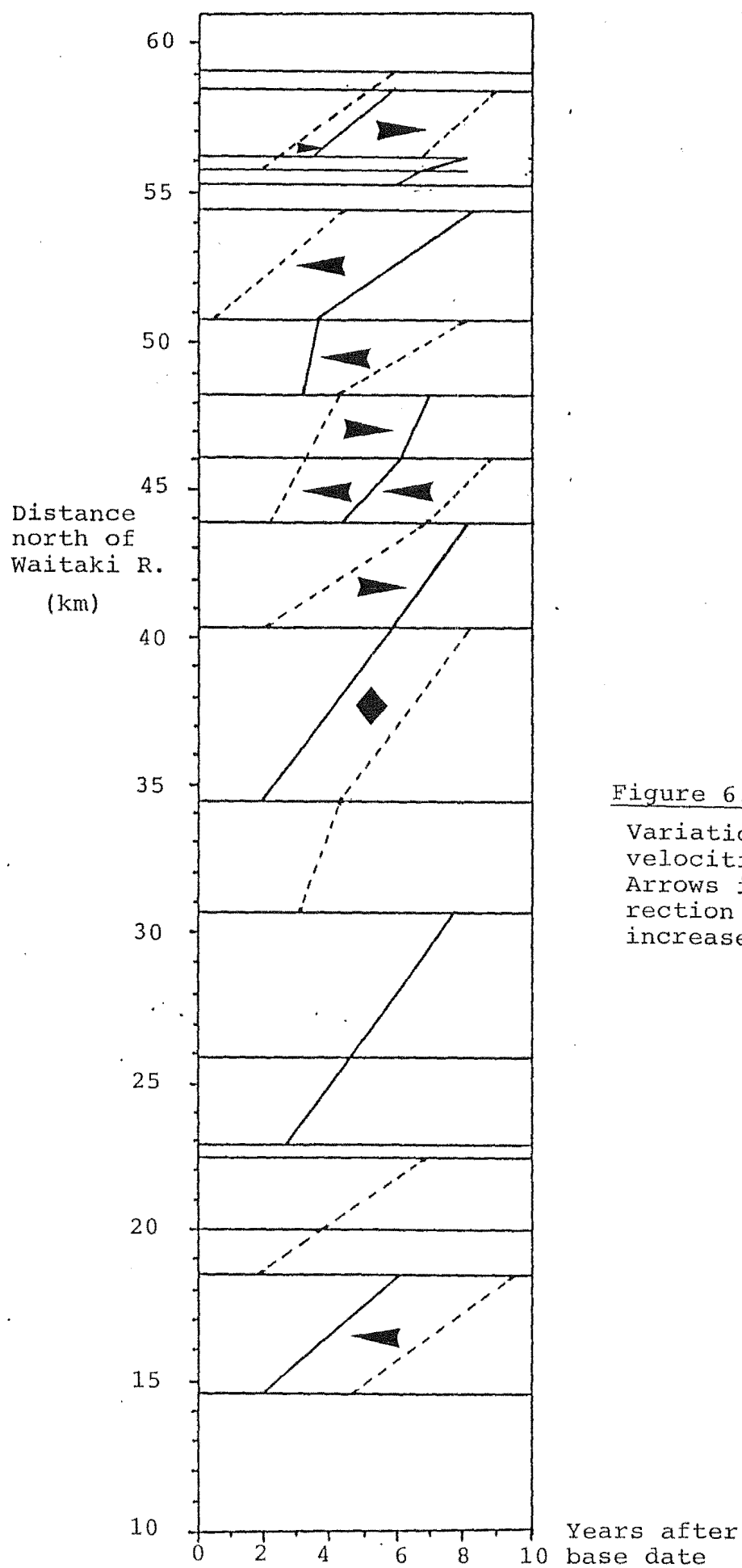


Figure 6.7

Variations in slug velocities over time. Arrows indicate direction of velocity increase.

Figure 6.8. The minima of the interpolations were taken to signify the base volumes of the foreshore profile. The curve above these points thereby represents the passage of slug volumes at the profile line. Converting the standardised values of the peaks and troughs to actual volumes gave the amplitudes of the volume fluctuations caused solely by given slugs of beach material (ΔB). The time period over which a profile changed from one extreme (maximum or minimum) to the other was used as a measure of half of the duration over which a profile was affected by a slug ($\Delta t/2$). It should be realised however, that because slugs appear to occur in irregular cycles, this may not be an accurate estimate of the effective duration of each slug. Figure 6.9 shows the effects of two slugs at a profile. Two situations are possible; (a) they may be separated by a period of time (producing a 'solitary' fluctuation followed by a long shallow trough), or (b) they may overlap if following close after each other (producing a 'bimodal' fluctuation).

The sizes and durations of slugs were calculated from all of the adjacent peaks and troughs that were linked in Figure 6.5. From this, it was found that the average maximum volume change caused by the passage of a slug of material (ΔB) is approximately 45 m^3 per metre of beach front, with a standard deviation of $27 \text{ m}^3 \cdot \text{m}^{-1}$. This represents an average of about one metre of progradation across the whole of the active beach. The average total 'lifetime' of a slug at any location (Δt) was found to average 4.9 years, with a standard deviation of 2.7 years.

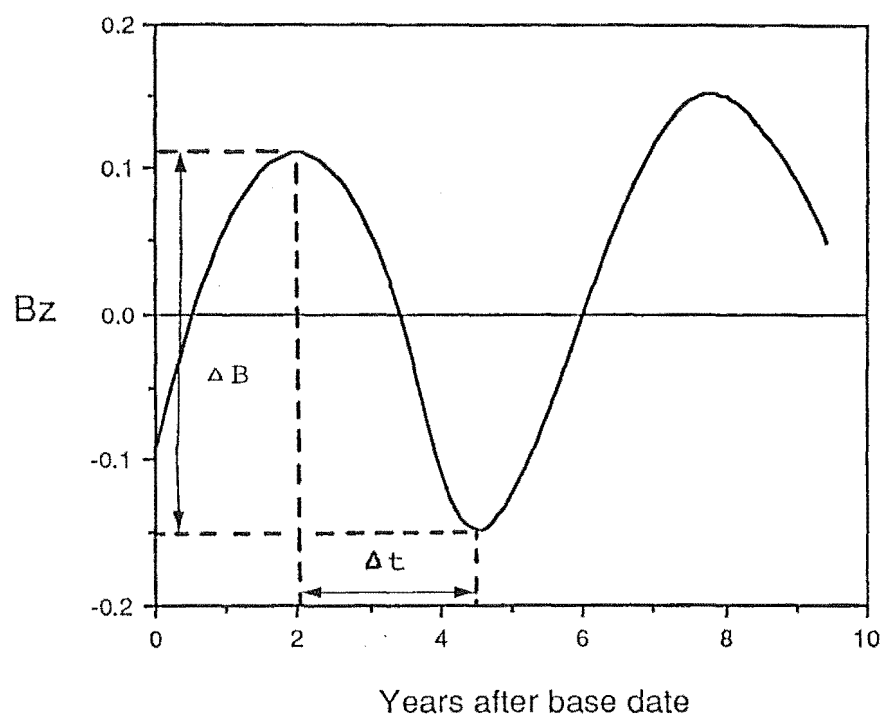


Figure 6.8 Criteria for calculating maximum volume range (ΔB) and duration (Δt) of a slug at a profile line. Ryans Rd. profile.

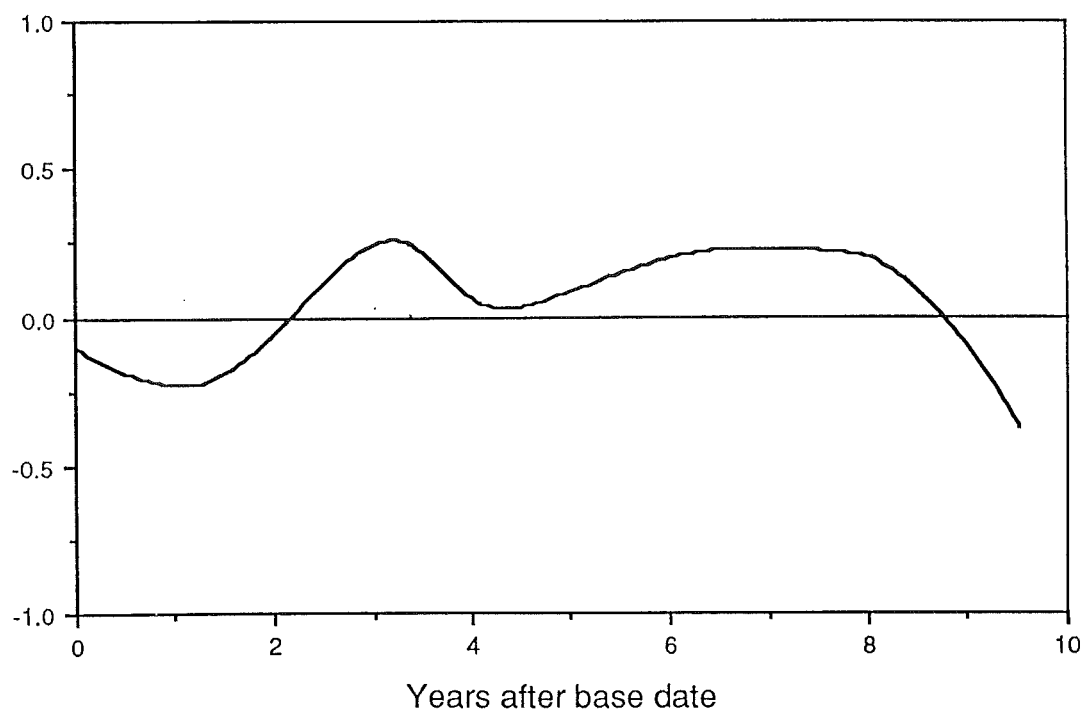
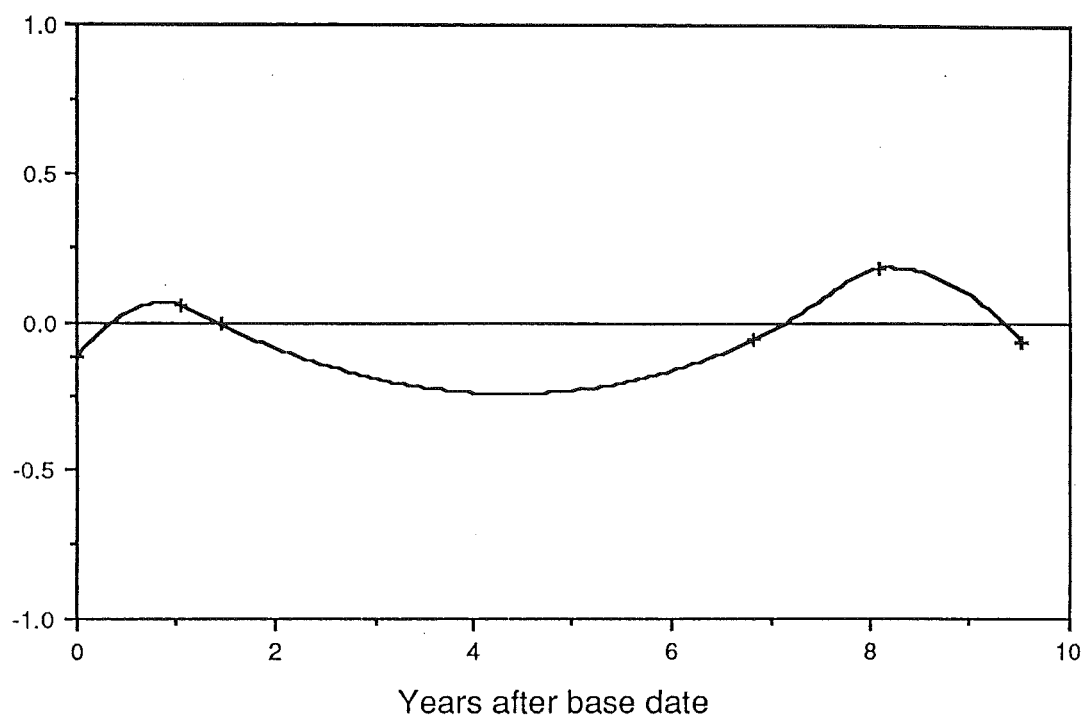


Figure 6.9 Pairs of slugs moving past a profile
(a) widely spaced over time - note the long duration of the trough. Craigies Rd. profile,
(b) closely spread over time - note the abbreviated trough. Lyaldale Creek profile.

This value also gives an estimate of the frequency of occurrence of the slugs. The length and total volume of the slugs along the beach cannot be accurately calculated from this, because the spatial and temporal variability of the rates of movement also affect the 'lifetime' of the slug. A knowledge of the changes in the total volume of slugs over time would have been very useful for determining the possible dispersion of them as they move alongshore. No pattern relating to this could be found from the changes in the volume range (ΔB) or duration (Δt) of the slugs.

It is clear from these results that the volume changes produced by the migrating slugs of material can be quite significant and prolonged. At the sizes and time scales given, the changes are not readily visible to casual observers and can only be revealed by intensive surveys of the foreshore morphology. Nevertheless, their effects may have major implications for the dynamics of the South Canterbury foreshore and coast. At Wainono Lagoon, for instance, overtopping of the barrier beach occurs at points where the foreshore is low in both height and volume. The adjoining lagoon and hinterland of the barrier may therefore be protected for some years from storm wave inundation by the presence of a slug of material that has been introduced to the foreshore from further south, and which enlarges the volume and the buffering ability of the beach. In other periods of years the lagoon and hinterland will be more exposed as a slug trough occupies the area.

Elsewhere along the coast, cliffs and backshores may be alternately more protected and then exposed in a similar manner to changing intensities of erosion and inundation. Future studies may reveal an ability to predict such changes by following the movements of the peaks and troughs in the beach volume from one profile to the next over a period of time. This could best be done by extrapolation from the linkages that were shown in Figure 6.5.

6.6 CONCLUDING REMARKS

The primary objective of this chapter was to develop a method for analysing the variations across all four dimensions of the South Canterbury mixed sand and gravel foreshore system. This has been achieved by measuring the changes over 10 years in profile volumes at 19 locations along the coast south of Timaru. It was hypothesised from the analysis that a portion of the total longshore drift material moves collectively as an above average volume, or 'slug'. No evidence could be found to refute this claim, and results show that the rates of movement of the slugs are strongly influenced by the prevailing angle of wave incidence at the shore. The approach has thereby revealed evidence in support of a phenomenon that was previously thought not to occur on the South Canterbury coast.

The greatest advantage of the overall approach used in this chapter is seen in the ability to present information on both the temporal and the spatial aspects of longshore sediment transport within a single framework. The inclusion

of time and space as two interdependent variables allows comparisons to be made within and between the movements of material through both. An additional advantage, and one that is important to the application of results to practical situations is that it makes a direct link between the phenomenon of longshore transport and the morphological effects on the foreshore at locations all along the coast. Many of the problems that have been encountered in previous approaches to analysing the movements of beach material alongshore have thus been overcome. The method is clearly capable of further refinement through careful selection of profile resurvey time intervals, by judicious location of profile sites, and by closer analysis of the results.

CHAPTER 7

CONCLUSIONS

7.1 SUMMARY OF MAJOR FINDINGS

This thesis has offered new perspectives for the study of longshore sediment transport on beaches, and particularly for the mixed sand and gravel foreshore system that occurs on the east coast of New Zealand. It has been demonstrated throughout the investigation that these mixed-sediment beaches are very different from the sandy beaches that are the focus of the coastal literature. Even so, many of the methods used in the present study have been successfully borrowed or adapted from approaches that were originally developed on sand beaches. Thus, the thesis proposition - that the rates of longshore sediment transport on sand beaches and mixed sand and gravel beaches are governed by distinctly different process environments, but can nevertheless be determined by basically similar approaches - has been maintained. Moreover, the four major objectives listed in Chapter One have been achieved. The major findings that have been established on the basis of these objectives are summarised below.

Earlier approaches to the study of foreshore sediment movements and longshore transport rates have been assessed in several ways throughout the thesis. In Chapter 2, methods that have been developed for

calculating rates of drift were seen to be of two types that fit neatly into the Process-Response framework of the investigation. One is based on the process inputs of the foreshore (such as the 'Energy Flux Method'), and the other is based on the morphologic and sedimentologic responses by beaches to longshore transport (such as the 'Littoral Barrier Method'). All of the methods were shown to present significant sources of error due to problems encountered in the measurement and representation of the complex field situation, and in the application of the results to other situations in time and space. Furthermore, it was noted that the inherent level of inaccuracy cannot be evaluated, since the 'true' value is itself indeterminable. The conclusion was reached that the diversity of the overall methodology for rate calculations has to some extent compensated for these deficiencies by enabling the application of several methods to any given situation, thereby improving the reliability of the final estimate, if only by defining a range of values.

On the South Canterbury coast, longshore transport has long been recognised as an important component of the sediment budget. However, the methods used in previous studies to estimate foreshore transport rates have been lacking in diversity, in accuracy, and in coverage through time and space. Essentially, the few estimates that have been made have related either to the long-term littoral barrier effects of Timaru Harbour, or to the longshore energy flux calculated from deepwater wave data and refraction analysis. Little attempt has been made in the previous studies to compare the two methods, though this

is widely seen as essential to attaining more accurate estimates and formulations.

The second objective of the thesis was to describe the process environment in which longshore transport occurs in a mixed sand and gravel beach system. This was achieved in Chapters 3 and 4, and was extended in the subsequent chapters. The foreshore zone was seen to comprise five subsystems possessing discrete process-response and sediment budget regimes that interact with those of adjacent subsystems. This perspective is believed to be more appropriate for process studies than the more common viewpoint in which first-order reductions of the foreshore environment are made with respect to energetic, sedimentologic and geometric factors. By this means the intricately related and contemporaneous influences of innumerable process factors at any location on the foreshore could be identified, and the variability of the process interactions across the foreshore were emphasised. It was found from this study that the paths of water movement along the foreshore as swash are of quite a distinctive nature in each of the subzones, and that this has an effect on the distribution and longshore movements of beach sediments.

The third objective, to apply several methods for calculating longshore drift rates to sand and gravel beaches, was fulfilled in Chapters 4, 5 and 6. The drift rate of the water mass was firstly assessed, from data obtained by dye tracing in a Littoral Environment Observation (LEO) Program that was undertaken on South Beach, Timaru, over a four-month period in 1987.

Multiple linear regression of the dye speeds against six other foreshore variables could account for only 30% of the total variance. It was concluded that the method gives neither a physical explanation of the water drift rates, nor a good indication of the dispersive swash flow on a mixed sand and gravel beach. It did, nevertheless, give a good indication of the directions of drift.

The rates of sediment transport along the South Canterbury coast were estimated in Chapters 5 and 6 over several time scales, using a number of different methods. Evidence was given in support of a net northward drift of sediment. The conventional Littoral Barrier Method was then applied to the 110-year accumulation record at South Beach, Timaru. The resulting 16 data points showed a linear trend in the accumulation rates that had been disrupted in periods when the littoral barrier was less effective as a trap. The average net rate of longshore drift was estimated from this trend to be $51,288 \text{ m}^3 \cdot \text{yr}^{-1}$. Annual variations were found to be within $\pm 25\%$ of this mean rate, while sub-annual storm and swell events were shown to cause counterdrifting, and rates of northward drift more than 100 times greater than the mean.

With the aim of enabling a realistic estimate of the longshore transport rate to be made solely from wave data, the dimensionless constant, k , of the 'Energy Flux Method' that has been developed for sandy beaches was 'calibrated' for the mixed sand and gravel beach situation, using two different methods. Long- and short-term accumulation rates (Q) that were measured at South Beach were compared with estimates of the longshore energy flux

($P_{\ell S}$) from refraction analysis and shore-based observations, respectively. These showed that the relationship between Q and $P_{\ell S}$ might not be linear, and is more than an order of magnitude lower than that occurring on sandy beaches.

In Chapter 6, the nature and rate of longshore transport was investigated using a new method that integrates the variability of the South Canterbury foreshore morphology through the four dimensions of time and space. Longshore variations in beach profile volumes over time were found to suggest the occurrence of longshore transport as collective units or 'slugs' of sediment above the base volume of drift. These slugs appear to move alongshore at rates averaging about 1.4 km.yr^{-1} that are dependent on the prevailing angles of wave approach. They are not visible to the casual observer, but are of such dimensions that they can have significant effects on the dynamics of the coast.

7.2 STUDY EVALUATION AND SUGGESTIONS FOR FUTURE RESEARCH

The final objective of this thesis was to note the implications of the results obtained for the sediment budget of the study area, and for future research in the field of longshore sediment transport. An overall evaluation of these provides an appropriate conclusion to the present report, and a useful starting point for future investigations.

With regard to the study of longshore sediment transport, the thesis has established and developed several lines of research. It has fulfilled the needs

for a more diverse methodological base and for an evaluation of the temporal and spatial variabilities of the drift rates along the South Canterbury foreshore. Very few studies have collectively applied more than one or two methods for calculating longshore transport rates under a single framework, in the manner that has been achieved here. Similarly, the high significance of the variability of transport rates through time and space has been elucidated to an extent that is not often observed in this field of research. More specifically, the study has successfully adapted sand beach methods for the evaluation of longshore transport rates in a mixed sand and gravel beach situation. It has also introduced a new method by which longshore transport and other phenomena may be viewed as integral components of four dimensional 'reality'. As noted in Chapter 1, this is an achievement that was claimed by Pethick (1984) to be highly desirable, but very difficult.

With regard to the mixed sand and gravel foreshores of the South Canterbury coast, the study has viewed the beaches in a way that is both valid and useful, but that has not been widely considered previously. The subzonation of the foreshore was shown to be of great significance to the development of the beach, just as the nearshore-foreshore-hinterland zonation is important to the development of the South Canterbury coast. Furthermore, an extensive data base has been created by the LEO program at South Beach (given in Appendix III), and evidence has been given for a phenomenon - the collective movement of sediment alongshore as a persistent morphological feature -

that has been thought previously not to occur on this particular coast.

The possibilities for future research that have arisen from the present investigation are innumerable. Two major themes in the research present the greatest potential for new perspectives in coastal studies. The first concerns specifically the findings given in Chapter 6. The occurrence of 'slug' movements on the South Canterbury coast was suggested, and supported by a limited amount of evidence, but was by no means fully defined. Further evidence might be obtained by a closer examination of the profile data, or from granulometric analyses related to the identified locations of the slugs. Improvements to the profile survey program are most likely to enhance the ability to assess the behaviour of sediment moving alongshore as slugs. This could involve the establishment of more profile sites and more frequent surveys, and a synchronisation of the surveys along the coast to within a period of less than a few days to allow more reliable interprofile comparisons. Once the pattern of shoreline change is better understood, the possible implications for coastal dynamics can then be assessed.

On a broader perspective, the subzonation of the mixed sand and gravel foreshore is seen to be of considerable scientific interest. Not only does it affect the patterns and rates of longshore transport, but it also exhibits other patterns of shore-normal differentiation that are less readily observed on beaches of smaller particle size ranges. It can therefore be used effectively to resolve a number of problems in coastal research. For example, particle transport and sorting processes under

rapidly fluctuating water flows, and morphologic changes caused by redistributions of sediment across and along the beach, can be examined and explained in terms of the across-shore variations. The foreshore subzonation thus presents many avenues for future research on the processes, responses and sediment transport régimes of beaches.

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APPENDICES

APPENDIX I SAMPLE OF RECORDING SHEET FOR LEO PROGRAM,
SOUTH BEACH

UNIVERSITY OF CANTERBURY

DEPARTMENT OF GEOGRAPHY

LITTORAL ENVIRONMENT OBSERVATIONS

Record all data carefully and legibly

YEAR

MONTH

DAY

TIME

87

1

21

1400

WAVE PERIOD

Record the time in seconds for eleven (11) wave crests to pass a stationary point. If calm record 0.

37

BREAKER HEIGHT

Record the best estimate of the average wave height of the seawardmost breakers to the nearest 0.1 metres.

0.3

WAVE ANGLE AT BREAKER

Record to the nearest ten (10) degrees the direction the waves are coming from using the protractor. 0 if calm.

90

BREAKER TYPE

0 - calm 3 - surging
1 - spilling 4 - spill/plunge
2 - plunging

4

WIND SPEED

Record wind speed to the nearest m/s. If calm record 0.

4

WIND DIRECTION

0 - calm
1 - N 3 - E 5 - S 7 - W
2 - NE 4 - SE 6 - SW 8 - NW

3

FORESHORE SLOPE

Record to the nearest degree the slope of the upper swash zone.

9

WIDTH OF SURF ZONE

Estimate in metres the distance from shore (upper limit of wetted beach) to seawardmost breakers. 0 if calm.

7

LONGSHORE CURRENT

CURRENT SPEED

Measure in metres the distance the dye patch is observed to move during a one (1) minute period.

5

DYE

Estimate distance in metres from shoreline to point of dye injection.

12

CURRENT DIRECTION

0 no longshore movement
+1 dye moves toward right
-1 dye moves toward left

-1

PLEASE CHECK THE FORM FOR COMPLETENESS

REMARKS (use sketches if helpful)

Harry Swanson
observer

APPENDIX II: INSTRUCTION SHEET FOR FILLING IN LEO FORMS

Gear required: recording sheet, clipboard, pencil, watch, anemometer, compass, abney level, straight-edged stake, methylene blue dye, tin, protractor.

Make all daily observations AT THE DESIGNATED SITE on South Beach.

Procedure:

- (a) Enter date and time of observation (24-hour system).
- (b) Wave period; the time it takes for 11 wave crests to pass an arbitrary, fixed point in the breaker zone. Timing begins when the first crest passes the point and ends when the 11th crest passes the point. ALL waves should be counted.
- (c) Breaker height; a visual estimate of the average breaker height (trough to crest) represented in the seawardmost major breaking zone. Move down the beach until line of sight appears level with the horizon, and estimate breaker height from there.
- (d) Wave angle; hold the protractor flat with the 0° to 180° line oriented parallel to the shoreline. Sight along the direction from which the seawardmost breakers are approaching the shore, and record the appropriate angle from the protractor.
- (e) Breaker type; (1) Spilling; wave crest becomes unstable at the top and breaks to flow down the front face of the wave, producing a foam surface.
 (2) Plunging; wave crest curls over the front face of the wave. 'pipeline', high splash, much foam.
 (3) Surging; wave crest remains unbroken while the base of the front face advances up the beach to break totally on the shoreline.
 (4) Spill/plunge; has characteristics common to both (1) and (2).
- (f) Wind speed; hold anemometer slightly above head level and record the average windspeed.
- (g) Wind direction; face towards the direction of strongest wind and record the compass (not the protractor) bearing from the 8-point code given on the LEO form.
- (h) Foreshore slope; place the straight-edged stake on the upper wetted part of the swash zone, pointing seaward. The level is placed on the stake and levelled by centering the bubble. Record the angle to the nearest degree.
- (i) Width of swash zone; visually estimate the distance from the shoreline (upper limit of wetted beach) to the seawardmost line of breakers (don't confuse offshore whitecaps with breakers).

- (j) Longshore current:
- (1) Dye distance; throw a container of diluted dye into the surf zone between the shoreline and the outermost breakers (aim for just land ward of the breakers). Visually estimate the distance from the shoreline (upper limit of wetted beach) to the point of dye injection and record.
 - (2) Current speed; mark the point of dye injection by sticking the stake in the sand. Follow the centre of the dye patch alongshore for a 1-minute period. Pace off the distance the dye travelled and multiply the number of paces by your pace length (in metres). Record this on the LEO form.
 - (3) Current direction; face seaward and note the direction of dye movement as stated on the LEO form. Note any obvious seaward movement in the remarks section.
- (k) Miscellaneous; record any unusual occurrences (e.g. waves approaching from more than one direction, recent erosion or accretion) or problems with observations, in the remarks section. Use sketches if helpful. Check that the form is complete and print the observer's name.

APPENDIX III: LITTORAL ENVIRONMENT OBSERVATIONS,
SOUTH BEACH, TIMARU. 8-1-87 to 14-5-87

Date	Day	Wave approach (degrees)	Hb (m)	T (s)	Breaker type	Swash length (m)	Foreshore slope (degrees)	Current velocity (m/s)	Wind speed (m/s)	Wind direction (° mag. N)
8/1	1	20	0.5	5.1	2	13	4	-0.033	5	135
9/1	2	0	0.6	10.6	2	15	5	0.067	4	0
	3									
	4									
12/1	5	0	0.8	6.8	2	12	11	-0.05	4	90
13/1	6	-10	0.8	4.4	2	12	15	-0.167	4	45
14/1	7	10	0.8	3.6	4	8	15	0.1	4	135
15/1	8	-10	0.5	4	2	8	13	-0.1	0	
16/1	9	-20	0.5	3.8	2	12	13	-0.167	7	45
17/1	10	0	0.7	5	4	10	13	-0.183	1	0
	11									
19/1	12	-20	1	4.6	2	15	10	-0.283	0	
20/1	13	-10	0.9	4.5	2	15	10	-0.583	7	45
21/1	14	0	0.3	3.7	4	7	9	0.083	4	90
22/1	15	0	0.7	4.3	2	10	10	0.317	7	135
23/1	16	0	0.7	4.5	2	15	10	-0.217	9	180
24/1	17	-30	0.4	7.9	2	15	17	-0.3	3	315
	18									
26/1	19	0	0.8	10.2	2	15	12	-0.3	4	45
27/1	20	0	0.8	3.5	2	20	10	-0.233	5	45
28/1	21	0	0.8	5.8	2	8	13	-0.333	0	
	22									
30/1	23	0	0.6	6	4	10	10	-0.267	5	135
	24									
	25									
2/2	26	0	0.7	4.1	2	15	10	-0.133	7	45
3/2	27	0	0.3	5	2	13	8	0	6	45
4/2	28	0	0.3	6	2	10	7	0.017	15	225
5/2	29	0	0.7	4.1	2	15	9	0.033	4	180
	30									
	31									
	32									
9/2	33	0	0.8	5.5	2	16	10	0.233	3	315
10/2	34	0	0.9	6	2	8	13	0.15	3	45
11/2	35	0	0.7	5.1	2	15	9	-0.3	0	
12/2	36	0	1	5.9	2	25	16	0	4	225
13/2	37	0	0.9	6	2	20	13	0.183	2	0
	38									
	39									
16/2	40	0	1.5	5	4	30	6	0.117	2	135
17/2	41	0	1.5	6.3	4	30	7		5	90
18/2	42	10	0.8	6.2	2	35	7	0.35	7	135
19/2	43	0	0.7	7	2	15	5	0.2	6	45
	44									
	45									
	46									
	47									
24/2	48	-10	0.5	4.8	2	10	21	0	15	45
25/2	49	0	0.6	3.5	2	12	20	-0.233	5	45

Date	day	Wave approach (degrees)	Hb (m)	T (s)	Breaker type	swash length (m)	Foreshore slope (degrees)	Current velocity (m/s)	Wind speed (m/s)	Wind direction (° mag. N)
26/2	50	0	0.5	6.7	3	10	11	-0.217	5	135
	51									
	52									
	53	0	1	10.3	2	15	8	-0.417	4	135
2/3	54	0	1	4.5	2	12	8	-0.533	6	90
	55									
4/3	56	0	1.8	9	4	25	7		10	135
5/3	57	0	1.5	12.4	4	25	5		3	90
6/3	58	0	1	7.6	4	30	6		5	45
	59									
	60									
9/3	61	0	1.2	9	4	20	6	0	4	135
10/3	62	10	1	6	4	30	7	0	3	180
	63									
12/3	64	0	1.3	7	4	30	5		4	45
13/3	65	0	0.9	6.3	4	25	6	0.067	2	135
	66									
	67									
	68									
17/3	69	0	0.8	6.5	2	25	5	-0.267	4	45
18/3	70	0	0.6	7.5	4	15	8	-0.167	5	90
	71									
20/3	72	-10	0.7	5	4	15	10	-0.267	8	45
	73									
	74									
23/3	75	0	0.5	6.6	2	12	7	-0.3	3	135
24/3	76	0	0.8	7	2	14	7	0.083	3	135
25/3	77	10	0.7	5.5	2	10	12	0.133	1	180
26/3	78	0	0.3	4	4	10	11	0.05	5	45
27/3	79	10	0.4	6	1	12	14	0	6	45
	80									
	81									
30/3	82	-20	0.5	3.8	2	10	7	-0.517	8	0
31/3	83	0	0.6	7.1	2	15	10	0.033	2	135
1/4	84	20	0.8	8.5	4	30	8		8	180
2/4	85	10	0.4	7.2	2	17	5	0.3	3	135
3/4	86	20	0.7	5.8	4	20	5	0.483	10	135
	87									
	88									
6/4	89	10	0.3	6.3	2	15	5	0.6	8	135
7/4	90	0	0.3	6.5	4	15	5	0.267	1	135
8/4	91	0	0.7	8	4	10	8	0.667	4	45
9/4	92	30	1	4.5	2	25	7	0.833	10	180
10/4	93	0	0.5	8	2	25	7	0.233	3	135
	94									
	95									
13/4	96	-10	0.8	9.4	4	10	9	-0.317	1	315
14/4	97	-10	0.6	5.8	4	12	8	-0.217	0	
15/4	98	10	1.2	4.4	4	15	9	0.967	11	180

